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STUDY ON INTRAFORMATIONAL DEFORMATIONS IN RECENT (QUATERNARY) SEDIMENTS - CRITERIA FOR DEFINING STRUCTURES PRODUCED BY SEISMIC ACTIVITY

by

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ABSTRACT

This study addresses deformation, in unconsolidated sediments, which may be potential indicators of paleo-seismic activity. It is based essentially on an evaluation of bibliographical information. The literature on this subject was examined in order to obtain information from both field observations and laboratory studies. General remarks on deformation of unconsolidated sediments and a discussion of their causes enable placing these phenomena in their context, defining them and to providing a number of classifications. An analysis of the literature reveals a few specific criteria, for certain types deformations as well as a number of general criteria. A chapter is devoted to a review of the literature on laboratory experiments conducted to produce ductile deformation. Finally, some recommendations are made concerning the nature of work which could be done as a follow-up to this study.

RÉSUMÉ

Cette étude porte sur les déformations intraformationnelles pouvant servir à titre de critères de séismicité. Elle est basée essentiellement sur une évaluation de données bibliographiques. La littérature sur le sujet a été examinée afin de trouver des informations tant sur les observations de terrain que sur les études en laboratoire. Des généralités sur les déformations intraformationnelles ainsi qu'une discussion sur les causes permettent de situer ces phénomènes dans leur contexte, de les définir et d'en présenter quelques classifications. L'analyse de la littérature permet de dégager quelques critères spécifiques à certaines déformations et aussi quelques critères généraux. Un chapitre est consacré à une revue de la littérature portant sur les essais en laboratoire exécutés afin d'obtenir des déformations souples. Enfin quelques recommandations sur la nature des travaux qui pourraient donner suite à cette étude sont formulées.

The opinions expressed in this report are those of the authors and do not necessarily reflect those of the Atomic Energy Control Board.

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CHAPTER I

TERMS OF REFERENCE AND WORK OBJECTIVE

INTRODUCTION

This research project was implemented under a contract awarded by the Atomic Energy Control Board of Canada to researchers in the Groupe de Géologie de l'ingénieur [engineering geology group] in the geology department of Laval University. It is the result of the Board's desire to increase its understanding of seismic activity. Such knowledge is indispensable for any agency whose objective is to ensure that the design of major structures, such as nuclear generating plants, meets all required safety standards and provides a reasonable guarantee of resistance to natural phenomena, such as earthquakes.

It is well known and has been clearly established that the region of eastern Canada, particularly central Quebec and the vicinity of the St Lawrence River, is one of high seismic activity. The location of the epicentres of most major earthquakes observed in eastern Canada since 1534 has been established in the publications by Smith (1962, 1964 [sic]). Figure 1 shows that the distribution of epicentres is not regular. However, it has long been the opinion that seismic activity is a regional phenomenon affecting almost all of the St Lawrence Lowlands. Recently, Basham et all (1979) systematically studied the distribution of epicentres and distinguished homogeneous zones of seismic activity (Figure 2). Moreover, this article contributed to a major change in the regional seismic probability map (Figure 3 - old map, 1970 edition; Figure 4 - new map, 1982 edition).

This new map recognizes that seismic activity in eastern Canada is not uniform, but is concentrated in certain sectors which could be isolated from each other. This idea of isolation of seismic activity zones is fundamental. It has major repercussions on theories of earthquake causes; these theories are imperfect and are currently the subject of constant discussion. Since this interesting subject is beyond the scope of our study, however, it will not be developed any further. Another important aspect of the notion of isolation or absence of relationship between zones of seismic activity is that the land separating these zones has little or no seismic activity. This condition is useful, since the absence or any seismic activity is a crucial factor in the design of major structures. However, this condition has not been positively established; in actual fact, it has only been established by negative reasoning. We know that, since 1534, there have been no major earthquakes in certain parts of the area (Nicolet, Trois-Rivières and so on), but we do not know what happened before 1534. Therefore, we have only a limited degree of confidence about seismic activity in areas which separate or surround so-called "high-activity" zones. The scarcity of information on seismic activity in these sectors stems from the fact that the definition of seismic zones is currently based on our perception of earthquakes since the

habitation of Canada by Europeans began in 1953. Observation of these pheonomena was initially restricted to inhabited regions and was limited by individuals' faculties of physical observation and their record keeping. Since the turn of the century, instruments that are constantly being improved have been providing observations of higher quality. However, our knowledge of the active zones, while constantly improving, is still very limited because it covers such short a period.

It is therefore important to work toward increasing our knowledge from information sources other than those that rely solely on the human and mechanical perception of earthquakes. Indirect methods based on the observation of earthquake effects would allow us to extend our observation period back in time to events predating 1934. This involves identifying indisputable permanent effects of earthquakes, clearly establishing the relationship between earthquakes and their effects, and observing these effects in the field and determining their geographic distribution. This would enable us to define homogeneous seismic activity zones with much greater precision.

The sediments of the Champlain Sea have covered a large portion of inhabited area, comprising the St Lawrence Lowlands, since the end of the last glaciation. These deposits have thus been in place for about 15,000 years and, since they can react to earthquakes, they may constitute reliable evidence of any seismic activity that has affected them since their deposition. This, then, is the framework of the study: an examination of the effects of earthquakes on Recent deposits, with the ultimate purpose of reaching a more precise definition of the zones of seismic activity in eastern Canada.

EFFECTS OF EARTHQUAKES ON SOILS

A soil subjected to earth tremors can be affected in various ways. These effects may be generally described as follows:

1. Deformation and reworking effects. The soil is deformed and its structure altered. In extreme cases, the structure or microstructure of the soil is completely obliterated and a new structure is formed. Where the effect is less intense, the structure or microstructure is hardly disturbed. In intermediate cases, the primary structures of the soil are preserved but are greatly deformed. New, secondary structures may be created. Our study will deal with this type of effect.

2. Alteration of the mechanical properties of the soil. The cyclical stresses caused by earthquakes have the long-term effect of latering the properties of certain types of soils (such as clay or silt). This type of effect is not well known or documented and will not be dealt with in this study.

The deformation and reworking effects with which this study is concerned are generally indicated by the term "deformation structure" or "intraformational deformation". We will see later that agreement on the exact meaning of these terms is not unanimous. We will also see that the possible origin of such "deformation structures" is not limited to a single cause. Unfortunately, earthquakes are not the only origin. Numerous and varied mechanisms can

result in deformations, for various reasons. In eastern Canada, for example, disturbances have often been observed in recent sediments. As this area underwent glaciation that ended about 10,000 years ago and as the climate at the end of glaciation was very cold, scientists have generally attributed the deformations to the effects of glaciation or freezing.

On the other hand, in countries which have not been recently glaciated but are regularly affected by earthquakes (Japan, California and so on), scientists have been able to establish, sometimes by direct observation, the relationship between sediment deformations and earthquakes. This relationship is sometimes so obvious, in the absence of other causes, that seismic activity is quickly identified as the cause without any effort at establishing criteria characteristic of the relationship.

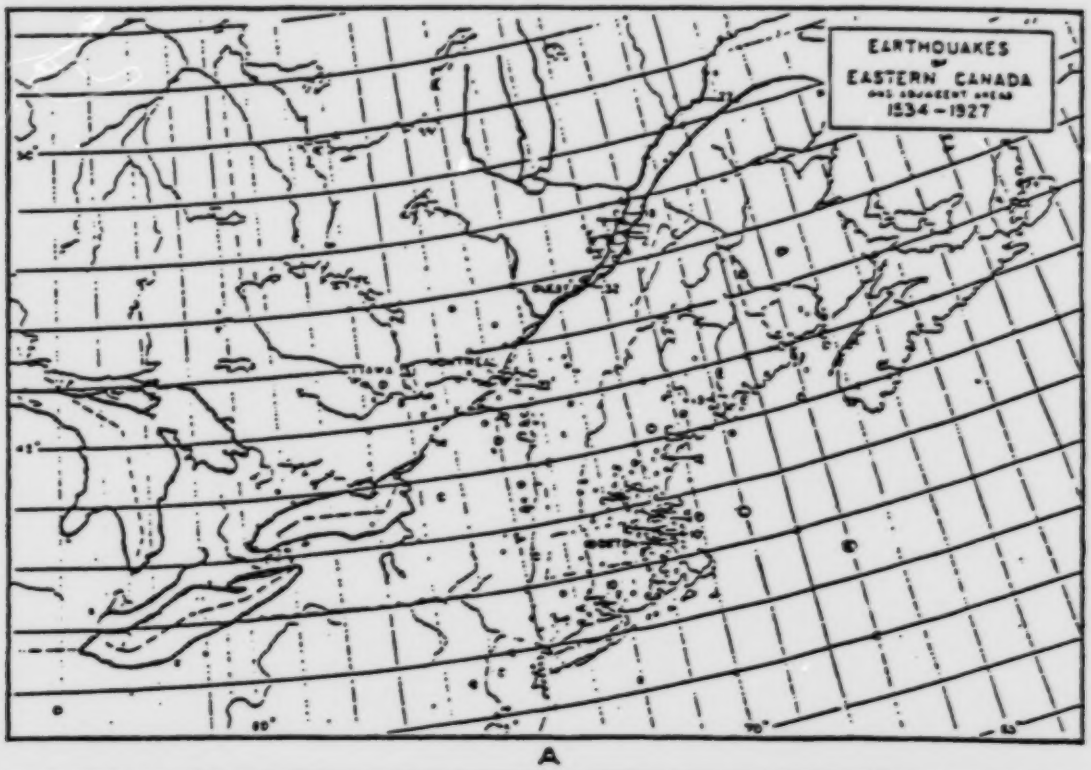
In eastern Canada, where there are numerous possible and plausible causes of deformations, it is essential to find or define criteria which will allow us to recognize the source of the deformations, especially if that source is seismic in nature. It would be surprising, in a region of which some parts are known to have pronounced seismic activity, if all intraformational deformations observed were caused by glaciation and freezing. We may logically expect to find a number of deformations resulting from seismic activity, especially in those sectors where such activity is strong.

OBJECTIVES OF THE STUDY

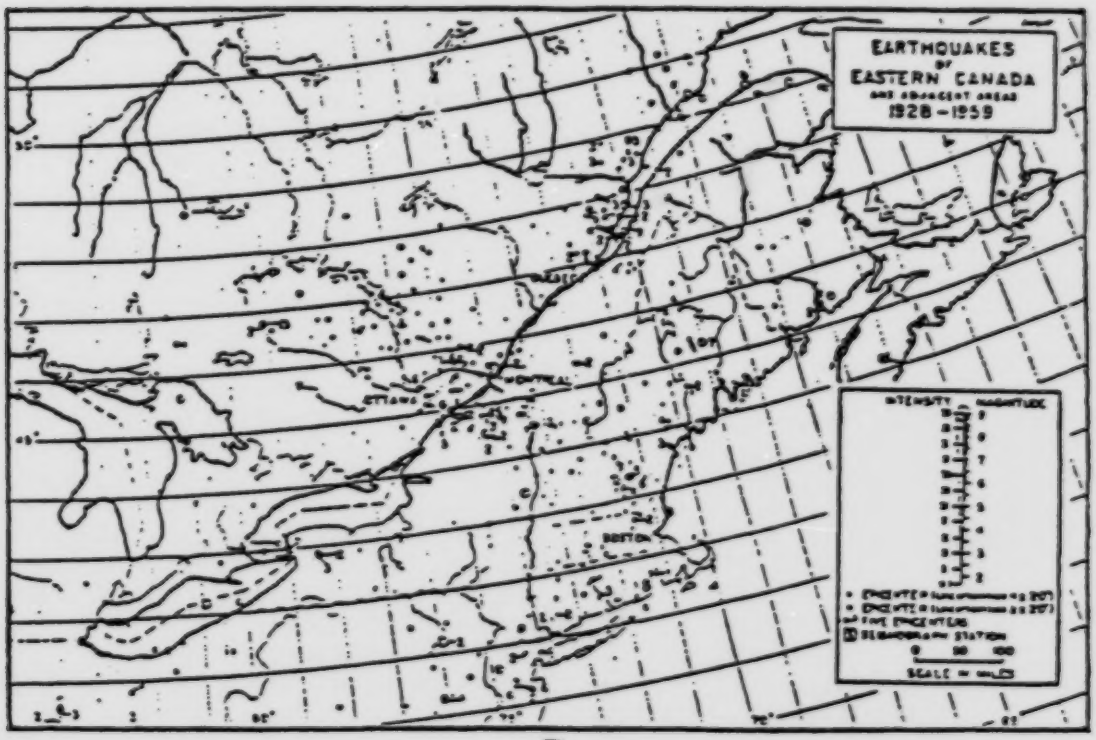
The primary objective of this project is to identify criteria enabling us to define the types of deformations produced by earthquakes in the soils and rocks. We are thus concerned with describing characteristics allowing us to attribute one or more types of deformation solely to the effects of seismic activity.

Secondary objectives inherent in the work method (discussed in Chapter II) involve establishment of a bibliographical inventory on the subject of deformations. This is not a matter of establishing a complete, exhaustive inventory, but of using a bibliographical search done as part of the project to draw up a partial inventory representative of the concepts described in the literature.

Another secondary objective is to produce a synopsis of knowledge on the subject of intraformational deformations. These deformations have been observed and described for a long time. Several authors have tried to determine their causes, some by analysing observations made in the field and others by using the results of experimental simulation in the laboratory. A few have attempted to classify them on the basis of various approaches. Nevertheless, the subject is not well understood and remains on the fringe of geology; this is suggested by the minimal space given to it in most textbooks. It belongs to a specialized area of geology, and most information is found in specialized journals. It will therefore be helpful to briefly summarize our current knowledge of the subject.



A



B

Figure 1 - Location of earthquake epicentres in easter Canada

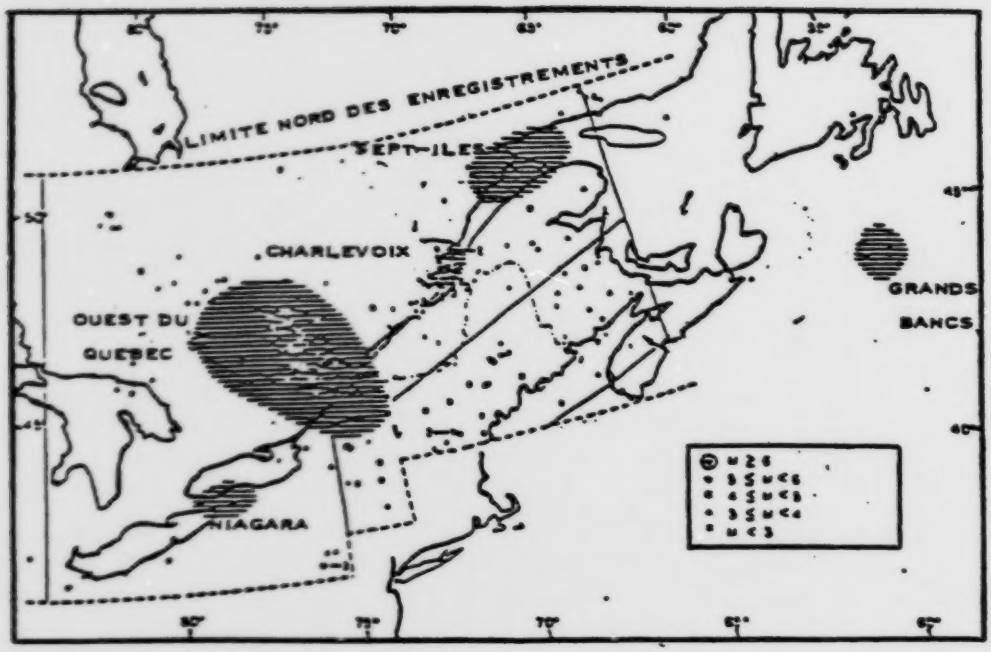


Figure 2 - Seismic zones in eastern Canada (from Basham et al, 1979)

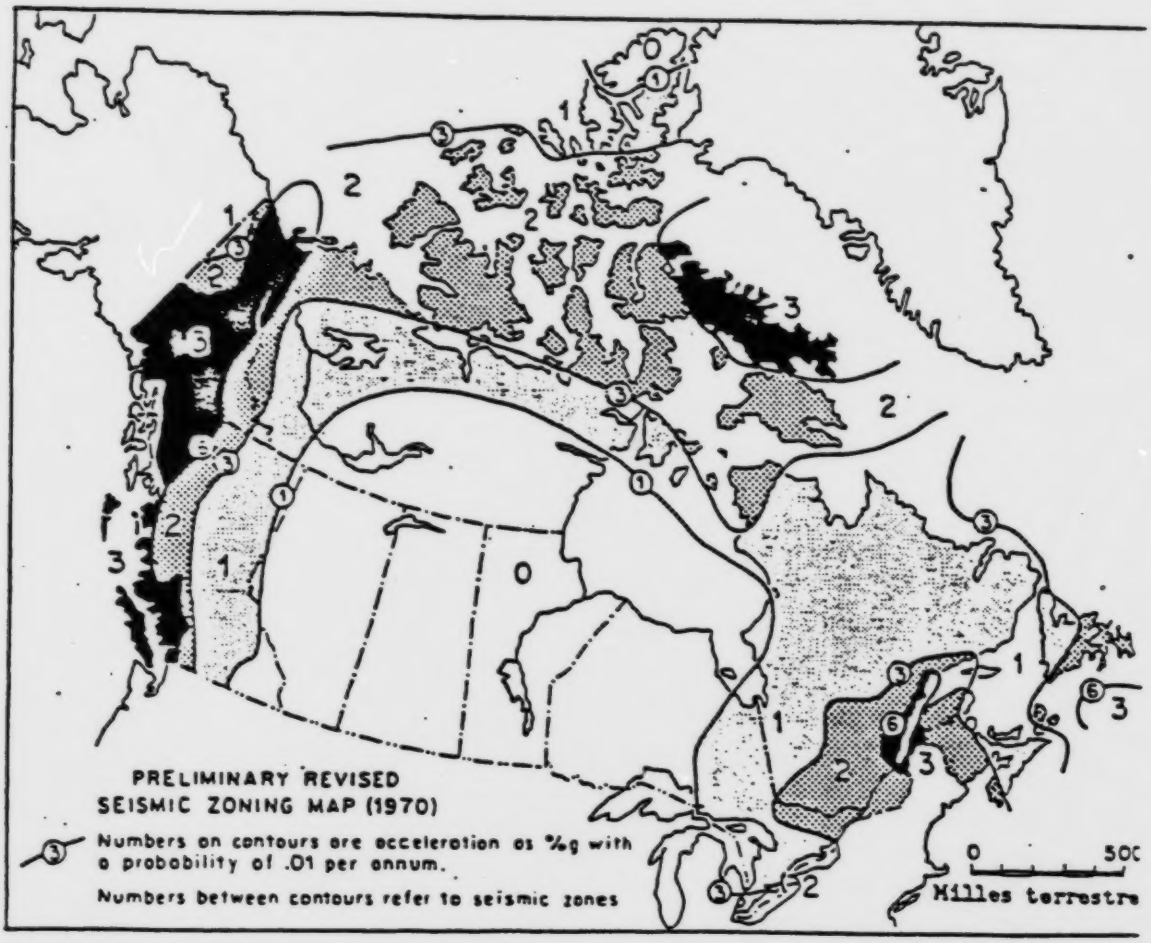

PRELIMINARY REVISED
SEISMIC ZONING MAP (1970)
Numbers on contours are acceleration as %g with a probability of .01 per annum.
Numbers between contours refer to seismic zones
0
500
Milles terrestre

Figure 3 - Seismic zones map of Canada (1970 edition)

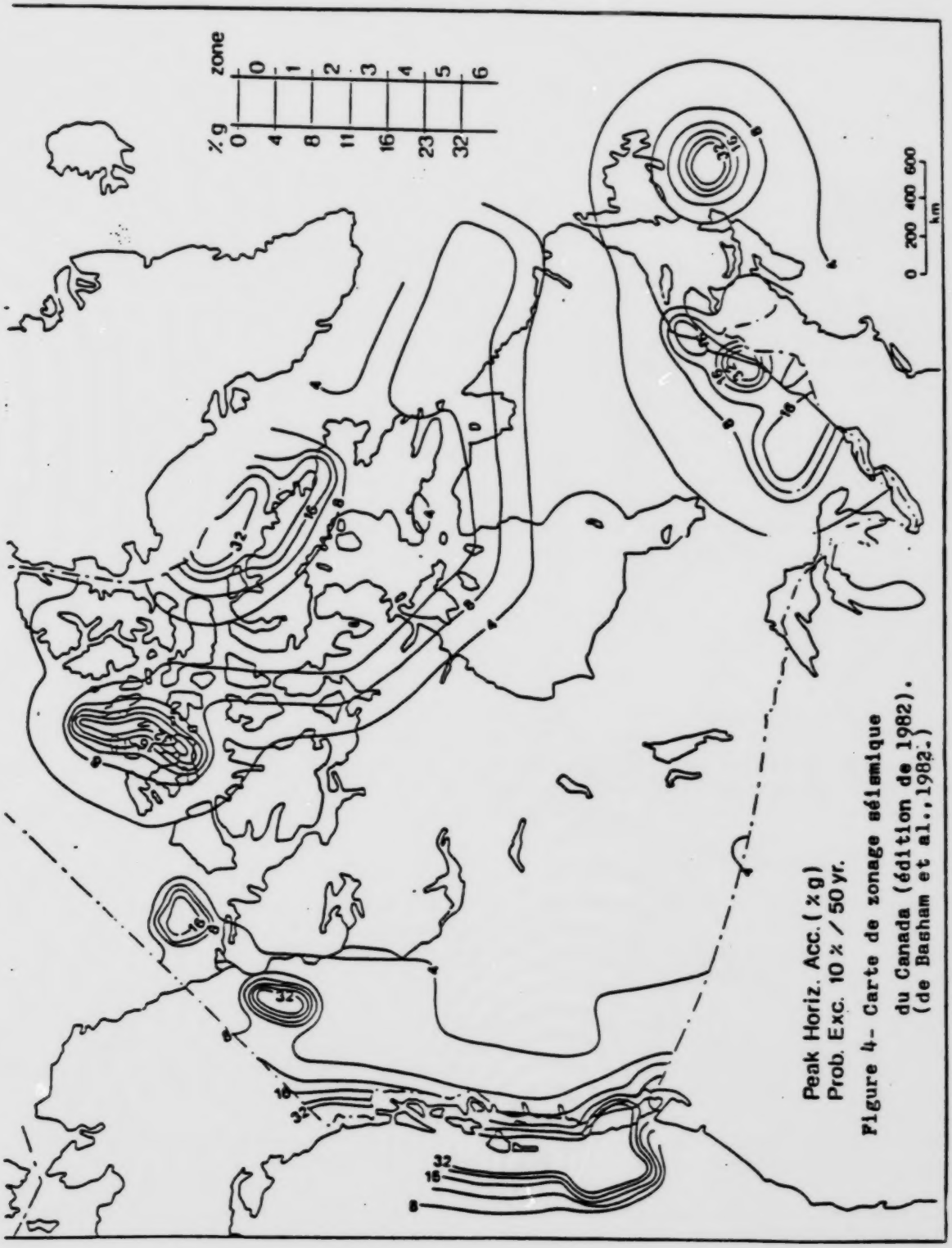

zone
0 1 2 3 4 5 6
%g
0 4 8 11 16 23 32
0 200 400 600
km
Peak Horiz. Acc.(%g)
Prob. Exc. 10 % / 50 yr.
Figure 4- Carte de zonage sélamique
du Canada (édition de 1982).
(de Basham et al.,1982.)

Figure 4 - Seismic zones map of Canada (1982 edition)

CHAPTER II

WORK METHODS

INTRODUCTION

Since a definition of the criteria sought can only be obtained by consulting available information, this project is based on a bibliographical search to produce an inventory of known data on intraformational deformations. There is a variety of information available: descriptive, analytical, experimental and so on. Only when this stage is completed can a synopsis of knowledge be done. It is thus important that this phase be well done.

A similar study has already been carried out by Sims (1978), who also established a relationship between intraformational deformations and earthquakes in California. Sims' work may therefore be considered as a starting point. However, the material sought by Sims differed somewhat from that of our study. Sims was mostly interested in "penecontemporaneous" deformations; he excluded structures associated with tectonic deformations, such as faults or folds. In fact, many writers describe non-tectonic structures as folds or faults.

Another useful source of information is Coates (1975) who, as part of a research project on intraformational deformations, compiled a bibliography. However, Coates' report is more limited and more selective than that of Sims.

We have carefully examined these two sources (Sims, 1978 and Coates, 1975), selecting the most relevant titles from each, especially Sims. (The bibliography prepared by Sims is annotated; the relevance of the titles given can therefore be determined.) The titles selected were ordered for examination.

BIBLIOGRAPHICAL RESEARCH

To complement the information obtained during examination of the references, we consulted the geoscientific data bank of the GEOREF system. At the same time, we did a more limited search, also through the GEOREF system, on the subject of clastic dikes.

These two research efforts through GEOREF are based on the use of key words chosen to clearly define the research theme and retrieve the greatest number of relevant texts. By using key words which could be combined in several ways, we obtained a surplus number of titles. In other words, several fields related to the subject under study were examined to avoid gaps. The result is that several of the titles retrieved were not really relevant and were rejected after analysis of the abstracts or actual texts.

This procedure, which deliberately produced titles that were not required, was a means of ensuring that the search was as exhaustive as possible.

There were 505 titles obtained during the bibliographical search on intraformational deformations using the GEOREF system. Incidentally, the

search applied only to texts published and catalogued after 1978. In fact, the publication by Sims (1978) adequately covered the period from 1819 to 1978. We therefore did not need to repeat this work.

The more limited search on clastic dikes produced 203 titles.

Finally, a conventional search, not involving computerized information banks but based on an examination of documents not usually catalogued in the banks (such as geological reports issued by federal and provincial governments or reports on local symposium) provided 35 more titles.

Thus, in addition to the titles cited by Sims (1978), the bibliographical search produced 843 titles.

To summarize, sources such as Sims and Coates gave us titles of publications concerning intraformational deformations. This information was complemented by a computerized bibliographical search and a conventional search. The result is that we had access to an impressive list of titles on the topic of research.

EXAMINATION OF TITLES

Document titles were scrutinized to eliminate all those which quite obviously had no relevance. This applied in particular to the GEOREF list, which inevitably contained titles mistakenly included. Furthermore, certain titles were found in more than one list, in that of Sims (1978) and in one or other of the GEOREF lists. These lists therefore had to be reconciled. All titles remaining after this filtering and reconciliation process were ordered for examination.

ACQUISITION OF TEXTS

The result of the bibliographical searches was that 378 titles were selected; these, according to their description, appeared to be relevant. We then ordered these titles from various sources. The main sources consulted were as follows:

- scientific library of Laval University;

- library of the Geological Survey of Canada;

- library of the US Geological Survey;

- internal libraries of the geology department (personal libraries) at Laval University;

- library of the Ministère de l'Énergie et des resources department), Quebec.

The most useful source was the library of the Geological Survey of Canada, which provided 88 texts; its staff photocopied the texts for us, a service that was very much appreciated.

The text acquisition phase was quite long, starting in October 1982 and ending in July 1983. Most of the required work was done by Mr. Michel Laverdière, hired for this project.

Of the 378 texts ordered, 338 were delivered. Forty texts are still not available. Examination of the missing titles indicates that most are in a foreign language (such as Russian, Japanese or Polish) and would thus not be comprehensive to us. Moreover, we do have texts by several of the authors whose titles are missing. During the analysis, we noted that many authors who have several articles to their credit tend to repeat or refine their ideas. Therefore, missing texts by authors from whom we have other publications are of less consequence. In the final analysis, there were seven texts which seemed relevant but could not be obtained.

ANALYSIS OF TEXTS

As soon as a text was delivered, it underwent a preliminary analysis to determine if it was really relevant and should be kept. If it was, information useful for a provisional classification of the article was noted and an index card (author, title, year, publication source and code) was prepared. Several articles with titles that were deceptive or did not clearly reflect the content were eliminated at this stage.

In a subsequent phase, a complete analysis of each article was done. We then attempted tc record all the relevant data of all the texts retained after the preliminary analysis. To guide this work, we prepared and used a coding sheet for the data. This sheet, which we wanted as complete as possible, is given in the Appendix. It was prepared, after a large number of the texts were read, with the project objectives in mind. Its use allowed coding of the information taken from the texts. Each code was then recorded in the file for the document and, through data processing, the information provided in each article could be sorted and compared. This work method was useful for synopsis purposes and proved practical. However, this kind of information sheet system has its limitations and is not sufficient in all cases. The analysis of each text was therefore completed with a commentary. This was especially helpful for general articles in which the authors dealt with several types of deformations. Where too many themes were treated in an article or book, all the coding parameters were used and the sheet ceased to be of use in sorting. In all cases, comments were stored for retrieval of the important points of each text analysed.

Almost all of the texts were analysed by the two persons responsible for the project and all texts were analysed by at least one researcher.

Finally, to fill in the gaps in the computerized file system, each of the authors also prepared specific notes on certain subjects.

There was an abundance of texts on deformation structures and intraformational deformations, particularly if those dealing with subjects related to these themes are included. IT was necessary to limit the documentation by eliminating titles dealing mostly with the topic of rock mechanics. For a number of years now, journals specializing in geotectonics have published numerous articles on the mechanical properties of liquefiable soils. Most of these articles did not really fit in with the theme of the project and were not selected; the only ones retained were those which dealt with experimental methods as applied to deformations.

CHAPTER III

GENERAL INFORMATION ON INTRAFORMATIONAL DEFORMATIONS

INTRODUCTION

The purpose of this chapter is to present a general discussion of current knowledge and views concerning intraformational deformations. This may seem superfluous and inappropriate in the context of this project; however, the subject is no little known and is generally dealt with in such a marginal fashion by "academic" texts and even specialized journals that it will be helpful to provide a rapid survey, with emphasis on certain subordinate topics, to avoid needless repetition later on.

The information provided here is taken from general books on the subject and specialized articles consulted during the bibliographical study.

CONTEXT

The concept of intraformational deformations is dealt with in general texts on sedimentology and stratigraphy and, to a lesser degree, in texts concerned with structural and/or tectonic geology.

In practically all of these texts, the treatment of the subject is superficial, for it seems to be considered of limited interest. Only a few books devote an entire chapter to it (such as Potter and Pettijohn, 1963; Collinson and Thompson, 1982; and Gubler, 1966). On the other hand, the number of articles published in specialized journals is quite large, and these articles are often devoted to a description of a specific kind of deformation. Few authors have dealt with themes such as classification and definition of deformations. In general, the deformations are described and the probably causes of the observed phenomena are discussed. There are few texts or articles providing an overall view of the subject. The bibliographical research published by Sims (1978) is a first step in this direction, for it allows a compilation of all elements useful in preparing a synopsis.

DEFINITION OF DEFORMATION STRUCTURES

Generally speaking, the terms used in defining a deformation structure are similar. However, certain authors have a limited view of the subject, while others offer broader definitions. The broadest definition that can be accepted is that deformation structures represent deformations of specific beds, whatever the origin and time of their occurrence. An intraformational deformation, on the other hand, is a deformation structure within a well-identified bed, without effect on the adjacent beds (above and below) and without regard for the causes or time of its occurrence. Few authors adopt such a broad definition and most of those who do add restrictions.

Potter and Pettijohn (1963), in a chapter on deformation structures, consider only deformations affecting the primary structures of rocks or sedimentary formations. They are more especially interested in deformations which occur during, or soon after, deposition. These are, therefore, truly

"penecontemporaneous" deformations. They thus exclude all deformations resulting from tectonic activity, chemical alteration and volume changes resulting from frost action and landslides or other soil movements. Pettijohn and Potter (1964) also offers a similar notion: [TRANSLATION] "These are deformations resulting from sedimentary phenomena that affect unconsolidated deposits, and not deformations of tectonic origin affecting previously indurated rocks." (p. 128)

Shrock (1948) presents a broader view, accepting structures formed before and after induration in his discussion of deformation structures. In actual fact, he considers both types, but treats them separately. This concept thus covers more than the previous one. In addition, it is not limited to structures resulting from purely sedimentary processes. Collinson and Thompson (1982) and Leeder (1982) devote an entire chapter to deformations and describe structures of various origins formed up to the moment of lithification. Broader definitions are found in structural or tectonic geology textbooks. For example, Billings (1954) uses this term to cover all deformations, regardless of origin. Hills (1963) does the same, attaching little importance to penecontemporaneous deformations. These definitions or concepts are very general, especially the latter, and cannot be used as a guide in the context of this project. It will therefore be relevant to list, and even illustrate, the types of deformations considered in this project and, finally, to discuss our concept of deformation structures as used in this report.

TYPES OF DEFORMATION

A number of deformation types will be described. In the interest of succinctness, this description will be limited to the main types, excluding the many known variations. Moreover, we will not attempt at this point to determine the cause or origin of deformations, even though some authors define a number of them in terms of their origins. This will be noted without comment, since this subject will be dealt with later in an exclusive section.

1. LOAD CASTS

This type of structure is sometimes identified by other names ([in French] figures de charge, moulage de charge). It is generally found in the lower part of beds of sand with interbedded clay. Load casts are sometimes found in beds consisting only of sand. They are formed when sediments are in the plastic state soon after deposition. They take the form of rounded pockets or pouches, occasionally with irregular protrusions. Their size varies from a few millimetres to several meters (Collinson and Thompson, 1982). Load casts rarely occur in isolation and generally cover large areas. The pockets are filled with sand, often slightly coarser than the sand of the adjacent beds. Internal structures can sometimes be distinguished in the sand within the pockets, in the form of wavy laminae. The underlying clay beds are deformed, especially under the pockets. These features indicate, according to those who have studied them, that these structures are the result of the force of gravity on beds of hydroplastic materials. The difference in density between the various materials apparently causes the formation of the structures. The term "load cast" implies that the origin of the structure is related to an overload. In this case, it is difficult to avoid referring to the origin.

Moreover, Kuene (1953) proposed the use of this name to designate structures formerly known as "flow casts". In his view, we cannot identify them without reference to their origin. The name has now been adopted by everyone.

Figure 5 illustrates the typical appearance of load casts.

2. BALL-AND-PILLOW STRUCTURES

The structures are also sometimes called [in French] "structures en traversin". They are generally found where a bed of san overlies a bed of silt or clay. The lower part of the bed of sand is separated into numerous elements of more or less spherical form resembling pillows. They are often aligned, with a lower convex part which penetrates the underlying bed. Their upper surface is flat. They are often very close together and limited to a specific bed (Potter and Pettijohn, 1963), while being completely absent from the adjacent beds. They consist only of sand and vary in size from a few centimetres to about two meters. They are normally found at the base of the sandy bed which has been deformed, while the upper part is intact. The underlying clay is greatly deformed and seems to envelop the pillows with a number of projections into the bed of sand.

These structures are found in deposits varying from Ordovician to Recent in age (Macar, 1948). They do not seem to be associated with any characteristic environment; rather, they are associated with specific conditions at the time of deposition. Keunen (1958) succeeded in faithfully reproducing these structures in laboratory experiments. He deposited a bed of sand over a bed of clay and subjected this combination to shocks. The sand dispersed, taking the form of pillows, and sank into the partially liquefied clay. It thus seems that the movement of the sand into the clay is vertical only.

Figure 6 illustrates ball-and pillow-structures.

3. PSEUDONODULES

This term, invented by Macar (1948), designates loaf-shaped or kidney-shaped structures having concentric or convolute stratification that generally parallels the outer envelope. Secondary minute folds can sometimes be observed in the central and upper parts of pseudonodules. These structures are formed of sand; they are sometimes found in isolation, but generally occur in groups in a clayey material. They are not linked to a bed of sand, although a sand layer is always found higher in the section. The clay enveloping pseudonodules is reworked and shows signs of major deformation. The longest dimension varies from a few centimetres to several meters.

Like ball-and-pillow structures, of which pseudonodules are an extreme case in the opinion of many people, formation is associated with a [TRANS] "vertical descent, which may or may not be accompanied by slight lateral movement, of a sandy sediment in a muddier, hydroplastic substratum as a result of local overloading" (Gubbler, 1966). The experiments of Kuenen (1958) also reproduced pseudonodules.

Figure 7 illustrates characteristic pseudonodules.

4. CONVOLUTE LAMINATIONS

These structures are also called [in French] "couches contournées" and, in English, "convolute bedding". They frequently occur in specific beds of sand or silt in various environments. They consist of stratification marked by undulations and irregular minute folding. The adjacent overlying and underlying beds are not disturbed.

An important feature of these structures is that the beds containing them have broad lateral continuity. Moreover, faults are never observed in them, even though the minute folding is extremely complex. Anticlines with narrow, acute crests are separated by rounded, spreading synclines. The lower part of the folds is sometimes in the form of a basin, while the anticlines may be shaped like domes. Considerable variation in form is observed.

The intensity of folding generally increases toward the top of the beds, starting from unaffected laminae at the base. At the top, the folds may progressively diminish or be abruptly cut off. The thickness of beds with convolute laminations varies from two to fifty centimetres. Formation of the convolutions involves plastic deformation of a partially liquefied sediment soon after deposition.

Figure 8 shows typical examples of these structures.

5. SLUMP STRUCTURES

This term ["structures de glissement"] is used consistently in French. In English, its usual equivalent is "slump structures", although it has several synonyms, such as "slide marks" or "slump marks". It has been used in the past to designate all sorts of structures, sometimes with great difference, some having no relation to slumping (Potter and Pettijohn, 1963). The word "slump" refers to lateral movements under the effect of gravity.
Ball-and-pillow structures and convolute laminations have been called slump structures.

True slump structures occur in abundance. They are frequently seen in glacial and glaciolacustrine deposits of the Pleistocene, as well as in older lithified materials. They occur primarily in interbedded sequences containing large quantities of fine-grained sediments. The most common forms are microfolds with acute crests, more or less recumbent, regular or irregular, affecting some beds only or an entire layer. The deformations may be continuous or discontinuous. They affect beds varying in thickness from a few centimeters to several tens of metres.

Figure 9 illustrates slump structures.

6. CLASTIC DIKES - SANDSTONE DIKES

Clastic dikes are, as the name implies, tabular masses of clastic material cutting other formations. They are sometimes called [in French] "structures d'injection" or "d'intrusion" ["injection structures" or "intrusion structures"], indicating that they were emplaced under pressure. A few authors include under this heading fillings of fissures by force of gravity

(Shrock, 1948). Such cases do not involve true dikes. The term "dike" is used in this report with the meaning given it in the context of igneous rocks; in other words, there is true injection of clastic material downward or upward. Moreover, this is the usual meaning (Potter and Pettijohn, 1963; Collinson and Thompson, 1982).

This type of structure has been observed for a long time and many descriptions are found in the geological literature. These dikes cut rocks of all ages, from Precambrian to Pleistocene. Clastic dikes invariably consist of sand, whereas the invaded material may vary in grain size from clay to coarse gravel. They vary greatly in size: they can be a few centimetres to several metres in width and may reach several kilometres in length in exceptional cases. Clastic dikes are generally vertical, with clearly defined and more or less parallel walls. Their source is often a lower sandy layer. The top is almost always truncated by erosion, although, in a few rare cases, clastic dikes have been seen linked to an upper sand layer.

Internal, strike-oriented structures, in the form of fairly well-developed laminae, are often visible, especially near the walls.

7. SAND VOLCANOES

These structures, which are uncommon by comparison with those already described, are seen mostly in sandy beds associated with clay beds. The material forming the volcanoes is usually fine sand. These volcanoes lie most often on clayey beds overlying beds of sand that show signs of reworking after deposition.

The volcanoes are in the shape of cones or domes, with diameters varying from ten centimetres to several metres and heights of about fifty centimetres. A depression in the form of a crater can be seen in the centre. Vertical sections in these volcanoes show the conical form and parallel nature of the internal layers. At the centre, a neck or chimney of sand can be observed, extending toward a lower sand bed. These volcanoes are rarely seen in rocks, but are frequently observed in unconsolidated surficial deposits soon after their formation. During earthquakes, a number of people have seen them being formed. Kuenen (1958) has reproduced them experimentally.

Figure 10 illustrates the formation of sand volcanoes.

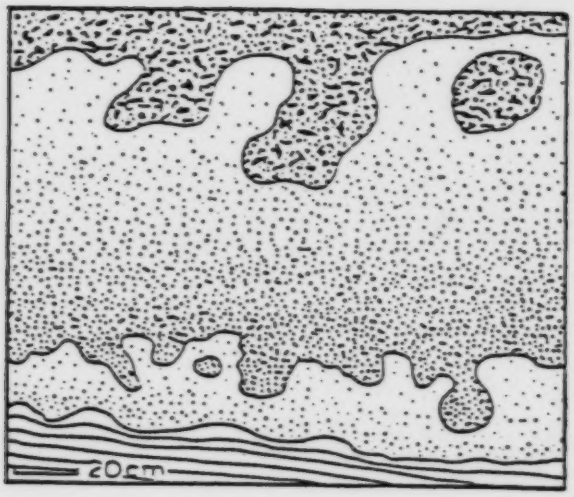


Figure 5 - Load casts (from Kuenen, 1953)

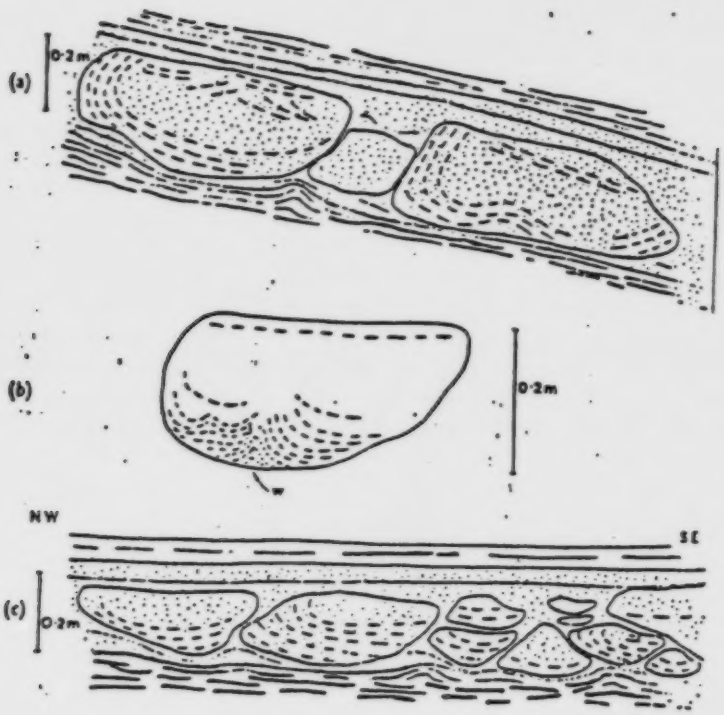


Figure 6 - Ball-and-pillow structures (from Weaver, 1976)

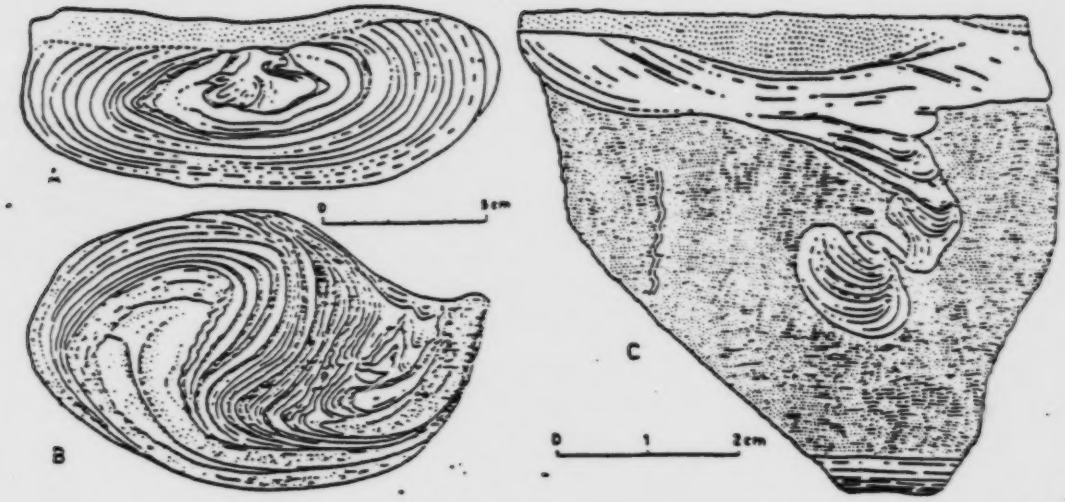


Figure 7 - Pseudonodules (from Kuenen, 1965, p. 31)

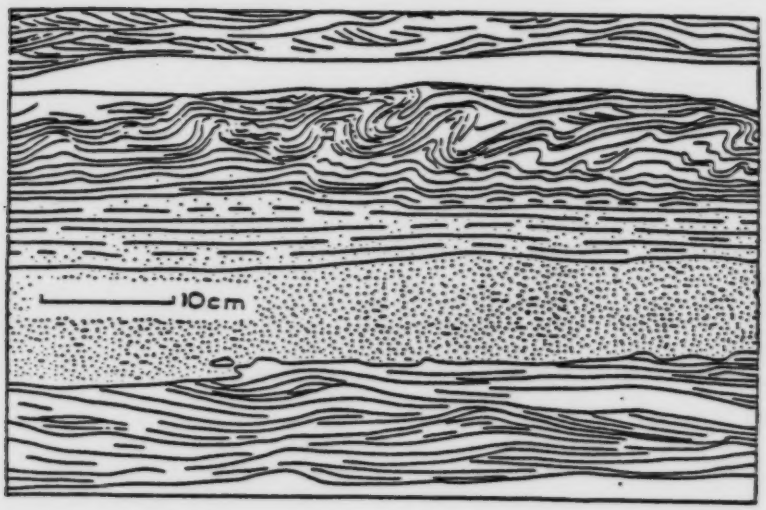


Figure 8a - Convolute laminations (from Kuenen, 1953)

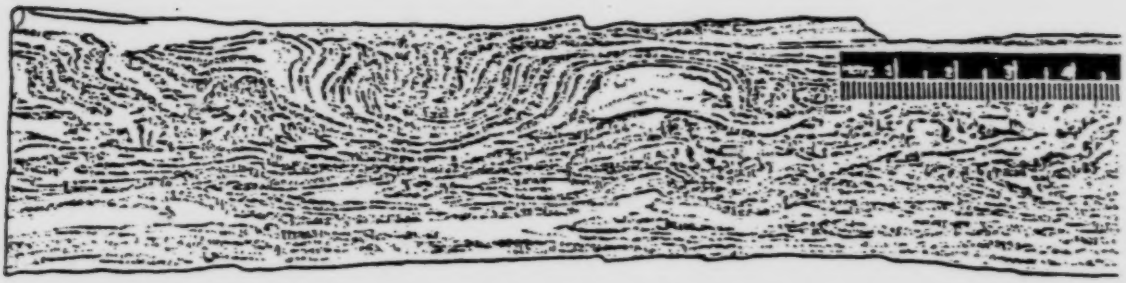


Figure 8b - Convolute laminations (from Potter and Pettijohn, 1963, p. 153)

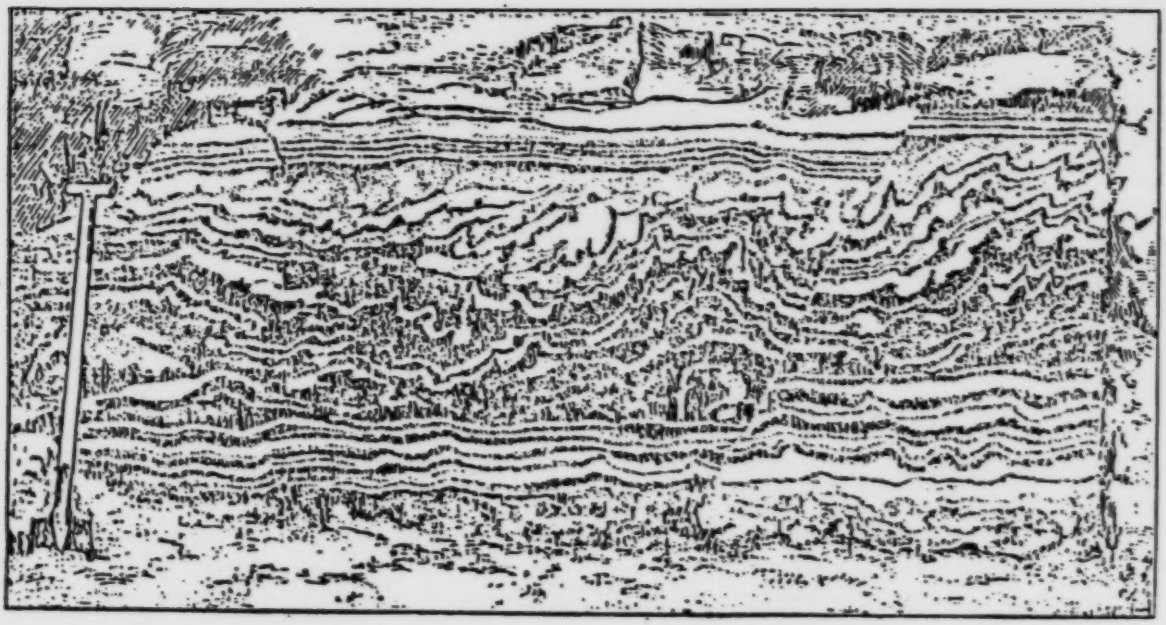


Figure 8c - Convolute laminations (from Potter and Pettijohn, 1953, p. 157)

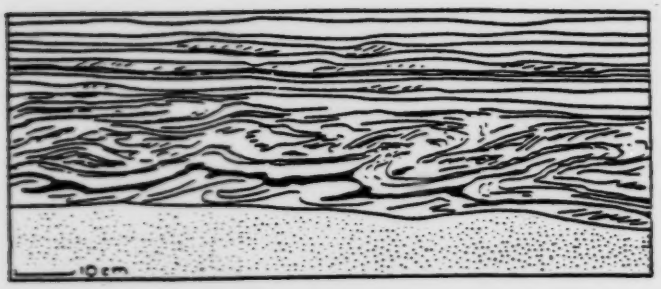


Figure 9 - Slump structures (from Kuenen, 1953)

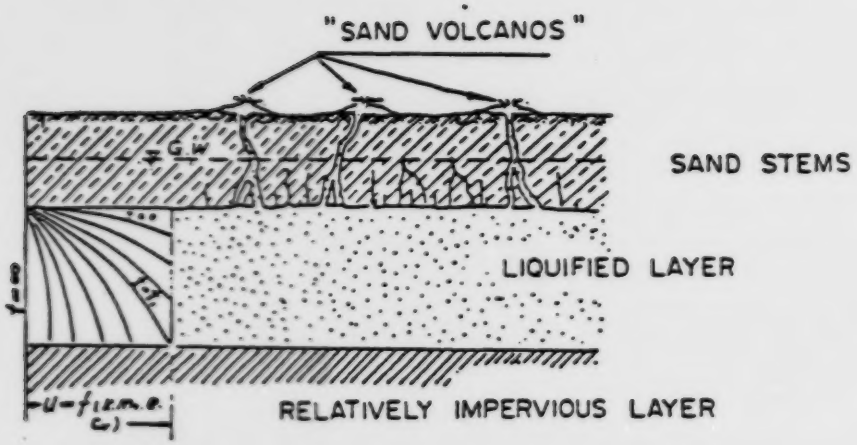


Figure 10 - Sand volcanoes (from Wang, 1983, p. 65)

8. STRUCTURES RESULTING FROM CLIMATIC PHENOMENA

To conclude this description of deformation structures, we add two types of structure associated with climatic conditions, such as cold and frost. These conditions currently prevail in the northern part of Canada and prevailed over all of Canada only a few thousand years ago. Structures associated with these conditions are abundant and are frequently observed and described.

A - ICE WEDGES - FROST WEDGES

These structures are observed in regions subject to frost action and, by definition, their origin is related to conditions resulting from the presence of frost. They are seen in glacial and glaciolacustrine deposits. In vertical section, they have the form of "wedges" that become thinner as they penetrate several metres downward. The cracks are filled from above with various fine-grained and coarse-grained materials, following a complex arrangement, generally in zones that are almost parallel to the walls. The fill material differs slightly from the adjacent material from which it comes. When it contains elongate pebbles, their longest axis is often parallel to the walls.

The cracks vary in depth from less tha 0.5 metres to more than six metres, but are usually between one and two metres deep. They vary in width from a few millimetres to thirty centimetres.

These structures are very important, as they are good paleoclimatic indicators.

Figure 11 gives a few examples of ice wedges.

B - FROZEN-GROUND STRUCTURES

Frozen-ground structures are also found in glacial and galciolacustrine deposits, and their origin too is associated with cold and frost conditions.

They are bedding deformations which take the form of buckling, publications and involutions, sometimes wavy. They have no regular structure.

The thickness of deformed varies from a few centimetres to several metres. In a number of cases, they are deceptively similar to convolute laminations and it is difficult to establish their nature with certainty. Extensive knowledge of the environment of the structures is required if we are to reach reliable conclusions.

Figure 12 provides a few examples of frozen-ground structures.

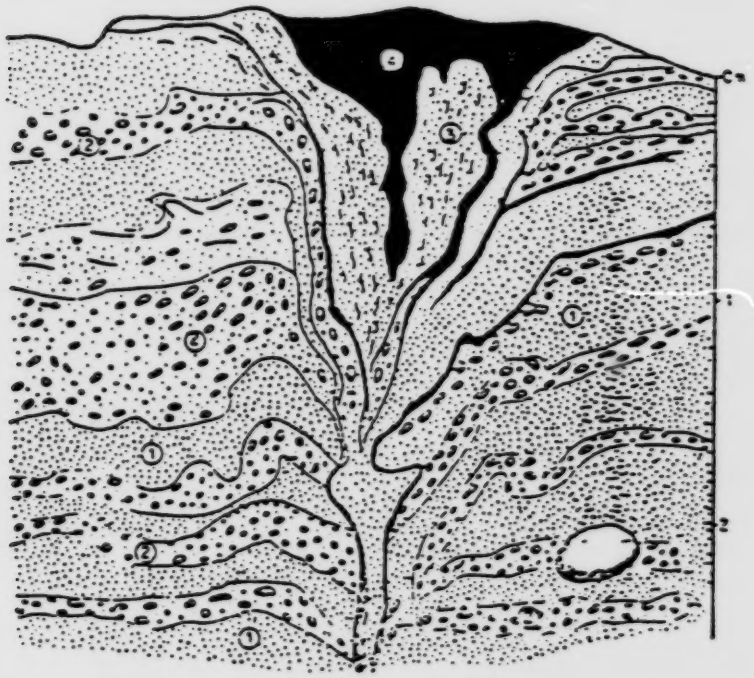


Figure 11 - Ice wedges (from Michel, 1975, p. 274)

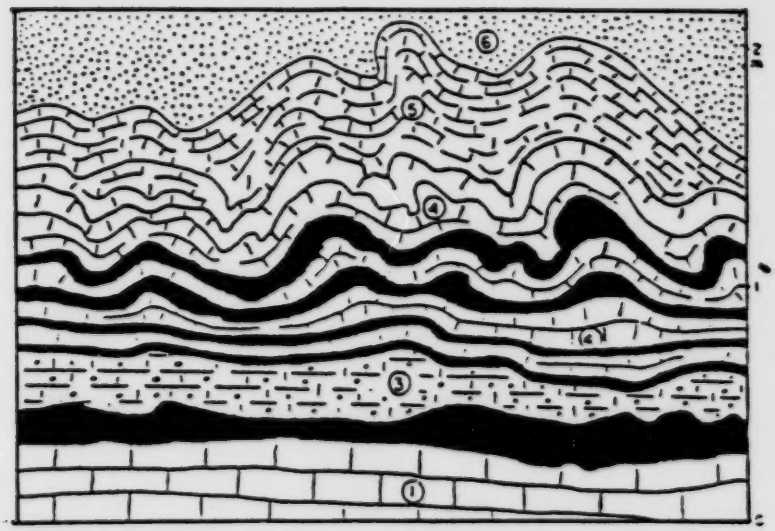


Figure 12 - Frozen-ground structures (from Michel, 1975, p. 292)

DEFINITIONS USED IN THIS REPORT

In this report, the term "deformation structures" will be used in a broad sense. In other words, it will not designate only primary sedimentary structures deformed during or shortly after deposition. The term will apply also to structures formed up to the time of lithification. Penecontemporaneous deformation is thus included, but other subsequent deformations during diagenesis are excluded. Moreover, this name has no genetic significance, in that the origin of structures is not taken into account. This is not always the case for specific structures whose names already have a genetic connotation. For example, the term "ice wedges" cannot be separated from a suggestion of origin.

Furthermore, the origin of deformations is not limited to the physical processes which normally accompany sedimentation and diagenesis. We take the view that tectonic effects are useful for study purposes, in that they can serve in establishing the criteria we are looking for. These tectonic effects are major folds, faults and, to a certain extent, some types of injection structures. We thus treat them in this report as we do the other factors studied.

We also use the term "intraformational deformations" to designate certain structures which affect a bed situated between two other beds that are unaffected by the deformation or deformations. This has already been explained. However, we do not limit ourselves to "intraformational deformations" and we do discuss structures which cut formations, such as dikes.

CAUSES OF DEFORMATIONS

The causes of deformations will be mentioned in a general way, without entering into elaborate discussions about the cause of causes of a given type of deformation structure. The purpose of this section is to present a synoptic view of known causes to help the reader follow the reasoning of subsequent chapters.

AGENTS

There are only a few natural agents identified as causes of deformations.

(a) Permanent agents

- Gravity: the force of gravity acts continuously on every body on the surface of the earth. Gravity can explain several types of structure of which it is the main actuating force, but it usually acts jointly with other factors to produce the effects studied in this report. Gravity affects both particles (compaction) and bodies (slumping).

- Density: the differences in density between various types of materials can cause deformations under the effect of gravity. Since the force

applied to a bed by another overlying bed is a function of density and gravity, variations in density lead to variations in stress. This is the cause of a number of deformation types; moreover, laboratory experiments have confirmed this.

- Tectonic forces: while these are not permanent agents over geological time, they may be considered to be so for the shorter periods of interest to us. Tectonic forces are directional stresses applied continuously to geological materials. They are studied mostly in relation to lithified materials - in other words, rocks - but their effects are also apparent in unlithified materials. They are responsible for phenomena such as folds and faults.

(b) Transient agents

These agents act in a discontinuous fashion while deformations are occurring. They may be regular, cyclical or irregular.

- Climatic effects: frost, heat. These effects act through various processes. The freezing of water contained in the soil causes changes in volume (expansion) which deform soil units in proportion to their water content. THe main effect of prolonged heat is to change the water content of the soil through evaporation, with a reduction in overall volume.

- Currents, waves: these agents act irregularly on the surface of soil layers. Currents drag particles in a ways that depends on their diameter and form. They therefore act selectively and can thus cause deformation structures. Waves act indirectly by creating conditions similar to those of currents.

- Earthquakes: earthquakes cause cyclical stresses on soil layers. These stresses are, to a point, similar to variations in the force of gravity (moreover, they are expressed in gravity terms). However, they are cyclical, rapid, directional and sometimes very strong. They affect both the soil and the water it contains. Earthquakes are frequently responsible for liquefaction phenomena and the secondary effects of this condition.

This brief summary covers the agents most commonly mentioned in the literature. We could add other agents less often observed (such as gas emanation), but these have little relevance. Finally, it is important to remember that these agents never act alone. In general, several operate simultaneously. Permanent agents have a continuous effect, while non-permanent agents are superimposed from time to time. For example, gravity acts constantly, while the cyclical stresses caused by earthquakes increase or decrease the effects of gravity, in addition to introducing their own effects. In most natural phenomena, the agents we have described produce a combination of individual influences.

NATURAL PHENOMENA INVOLVED

There are many natural phenomena involved in producing deformation structures. They always concern at least one permanent agent, and often two, or a permanent agent and a transient agent. The following are the main phenomena found.

1 - Vertical movements

(a) Consolidation - This term is used here with its soil mechanics meaning: a change in volume, mainly from the effect of gravity. The soil particles assume a more closely packed configuration through a reduction in void volume. The result is a distinct decrease in total soil volume. Other agents can speed up this process. Anything which might add to the weight of the soil (such as a glacier or fill) will contribute to intensification of this process.

(b) Compaction - This term describes a reduction in volume through removal of a component of the soil, usually water and sometimes oil. The volume occupied by the removed material is replaced by a rearrangement of soil particles. In this way, the volume is reduced. The removal of material may be natural (evaporation, absorption of water by plants or natural drainage at the edge of a slope) or artificial (pumping).

2 - Lateral movements

(a) Sliding - This movement results mainly from the effect of gravity upon a mass whose geometry favours movement along an inclined plane. In this type of phenomenon, the horizontal component of the movement is generally greater than the vertical component. Several deformation structures are attributed to sliding.

(b) Material transport - Various environments can contributed to the transport of material that is then deposited. Deposition may be close to the source, with complete reworking of the displaced material. The agents involved in transport are, in order of importance, water, ice and wind.

TIME OF DEFORMATION

We must be able to determine the time at which a given material is deformed at a precise point in its evolution if we are to understand its nature. This is not sufficiently emphasized in the literature, although it warrants some discussion.

In fact, deformations resulting from any agent will vary according to the stage during which a formation is affected. For example, a major vibration will resuspend a newly deposited sediment that is still saturated and unconsolidated. The main effect will be a reworking of the material, without preservation of any evidence of the initial structure. If the material is at a later stage in its diagenesis and is slightly consolidated, the same vibration may produce deformation structures of the "load cast" type, involving differences in density of the materials affected. If the material is even further along in its diagensis, the vibration might only cause compaction.

These various effects result from the different behaviour of soil at various stages of its diagenesis. A soil that is young, soft and saturated may easily be resuspended or completely reworked. An older soil that is partially consolidated will show plastic behaviour and will be deformed. A more evolved soil, one that is firmly consolidated, will display elastic behaviour and

will break along well-defined rupture planes. The same cause will thus produce different effects, for these reasons. It is obviously difficult to specify the movement of deformation and the state of the soil at that movement if we observe it after lithification, but it is possible. Few authors in the literature make distinctions of this kind. Some do so indirectly, only dwelling on penecontemporaneous deformations and excluding tectonic effects. In this report, we cover deformation structures characteristic of the following three stages:

- deposition or syngenesis;
- post-deposition or diagenesis; and
- post-diagenesis or lithification.

CLASSIFICATION

[Original English quotations]

> The classification of structures due to intraformational disturbance is troublesome. These structures are difficult to define and describe independently of their origin. And the origin of many is even yet unknown or poorly understood. Yet a classification independent of origin is virtually meaningless.
>
> Potter and Pettijohn, 1963, p. 144
>
> The terminology and classification of physical sedimentary structures which have developed in the past decade reflect some confusion of description and genetic factors ... Most classifications of all such structures masquerade as descriptive, yet all contain strong genetic pre-judgements. Load cast, load flow and simply load structure imply knowledge of gravity loading, i.e., are in fact genetic terms.
>
> Dott, 1962, p. 117

These two quotations illustrate the problems raised by classification of deformation structures. Several authors mention that the ideal classification would be a purely descriptive one that made no illusion to or implied anything about origin. Others, however, prefer to use a genetic type of classification, one based on the causes of structures. Davies (1965) writes that this type of classification is the best and the most natural. However, as noted by Potter and Pettijohn (1963), a genetic classification can be difficult to achieve if the causes are poorly understood.

The analysis of documents indicates that two main types of classification are used:

1 - a global classification of structures - all known structures are included in its; and

2 - classification of specific structures - a classification is developed for a well-defined type of structure (such as clastic dikes).

Each of these types can be established on the basis of different criteria, of which the most common are:

(a) form, geometry or morphology of structures (descriptive or morphologic classification);

(b) origin, causes (genetic classification); and

(c) mixed basis, containing elements from (a) and (b); in other words, forms and causes (mixed classification).

Following are a few examples of the classification types mentioned.

1 - Global classification

A few authors have attempted to classify all structures, and most have adopted mixed classifications. However, some have tries to stay within either a descriptive classification or a genetic classification.

An example of a descriptive global classification is that developed by Potter and Pettijohn (1963). It is based on the relative importance of lateral and vertical displacements and on the severity of deformations of original beds; eight levels are distinguished:

(1) undeformed bed;

(2) bed with load casts at the lower surface only and with vertical movement only;

(3) ball-and-pillow structures, after a complete or partial breaking of the bed;

(4) asymmetric load casts with vertical and lateral displacement;

(5) convolute laminations, confined to one bed, with vertical and lateral displacement;

(6) slump structures involving more than one bed, with lateral displacement;

(7) slide breccias, broken bedding and lateral displacement; and

(8) injection of material (dikes, sills).

This kind of classification encompasses all the types of structures recognized by Potter and Pettijohn and does not involve origin. It is one of the rare examples of this type found in the analysis of texts.

Shrock (1948) also used a descriptive classification, although it was based on the position of a structure within a bed:

- structures formed near the top of the bed;

- structures entirely within a bed or affecting a series of beds in a general zone;

- structures beneath the lower part ("undersurface") of a bed, affecting the underlying strata.

He then describes the forms observed in each category. We should mention that Shrock treats clastic dikes separately, classifying them by formation mechanism.

Most authors who attempt global classifications seem to prefer the genetic approach and there are many examples of this type. A few are given below.

Twenhofel (1932) offers a simple classification based on formation mechanisms in crder of probable importance:

- slumping;

- compaction;

- lateral movement caused by pressure of overlying sediments;

- thrust from surface agents;

- recrystallization;

- removal of material.

Nagtegaal (1965) developed a purely genetic global classification. It is given in Table I. It will be seen that structures are grouped according to whether they were caused by currents, chemical processes, diagenetic differentiation and so on.

Conybeare and Crook (1968) also provided a genetic classification of all structures. They designated structures with names of rheotropic structures, distinguishing them on the basis of the behaviour of the material deformed: for example, quasi-liquid behaviour (sand volcanoes, clastic dikes), hydroplastic behaviour (slumps, ball-and-pillow structures, convolute laminations, load casts) and quasi-solid behaviour (ice wedges).

Finally, the most complete global genetic classification is probably that of Collinson and Thompson (1982). It is used in presenting and describing each structure (p. 136). Three large families of structures are identified by nature of origin (physical, chemical or biogenic). Each of these classes is then subdivided. The subdivisions of deformations caused by physical processes are based on how the structures are positioned at the surface and within the beds and, finally, on whether they affect more than one bed.

TABLE I

[RETRANSLATION]

CLASSIFICATION OF NON-ORGANIC SEDIMENTARY STRUCTURES

1 - SYNDEPOSITIONAL STRUCTURES

1.1 - With current-oriented elements - elements parallel to the current, perpendicular to the current - imbricate structures - random orientation

2.1 - Current-oriented morphologic units

1.2.1 - inclined stratification, cross stratification

1.2.2 - lenticular forms, ripple marks

1.2.3 - erosion structures

1.2.4 - deformation of laminae by current - convolutions (Kuenen) - lineations of load casts

1.3 - Horizontal stratification (bedding)

1.4 - Structures resulting from redeposition en masse - mud balls - breccia structures

1.5 - Structures resulting from chemical processes

1.5.1 - chemical accretion

1.5.2 - residual structures

2 - METADEPOSITIONAL STRUCTURES

2.1 - Clinostructures
boudinage - breccias - convolutions - décollement - olistrostrome - sand volcanoes - slumping

2.2 - Imprints
mud cracks - fulgurites - and so on

3 - POSTDEPOSITIONAL STRUCTURES

3.1 - Structures attributable to diagenetic differentiation nodules - cones - geodes

3.2 - Structures attributable to deformation and displacement
ball-and-pillow structures - clastic dikes - convolutions - cylindrical structures - load casts - mud volcanoes - and so on

Translated [from English to French] and adapted from Nagtegaal, 1965.

CLASSIFICATION OF SYNDEPOSITIONAL DEFORMATION OF SEDIMENTS

TYPE OF MOVEMENT	STRUCTURES
MOVEMENT OF AIR OR GAS	Air heave, gas pits, mud volcanoes
MOVEMENT OF WATER ABOVE SEDIMENT LINE	Convolute bedding, oversteepened current bedding etc.
WATER MOVEMENT WITHIN SEDIMENT LAYER	'Point up' structures etc.
MOVEMENT OF THE SEDIMENT Dominantly Vertical Movement	Load casts Ball and pillow structures Raft and shale diapir structures
MOVEMENT OF THE SEDIMENT Dominantly Horizontal Movement	Unconsolidated – semi consolidated sediments *Sheet Slides:* *(a) Thin sheet slides : thin folded sheets* *(b) Thin sheet slides : sandstone ball sheets* *(c) Thin sheet slides : sheared slab sheets* *(d) Thin sheet slides : chaotic slab sheets* *(e) Thin sheet slides : distended by gravity* *(f) Extensive thick slides : Fisherstreet type* *(g) Extensive thick sheet slides : Ross type* *Shearing Slides* *(a) Simple rotational Shears* *(b) Complex sheets of rotational shears* *(c) Chaotic sheared sheets* Chaotic slides of fragmented consolidated rock *Reef talus slides* *Chaotic Basin margin conglomerates and breccias* *Chaotic mountain front slides*

TABLE II - Classification of deformation structures, by Gill (1979)

A few authors have developed classifications which may be qualified as mixed, since they contain elements of each type. For example, the classification by Gill (1979), summarized in Table II, groups structures in terms of the type of movement of the agent responsible for structure formation (water, air, gas or solid) and in terms of the horizontal or vertical components of movement. A notion of mechanics is therefore implicit. However, to present the phenomena classified, he sometimes uses terms that are descriptive (such as "mud volcanoes") or genetic (such as "air heave").

The other type of classification is limited to specific structures. In fact, a number of authors are interested in only one pattern of structure, which they classify using subdivisions based on form or origin, as for the first type of classifications are more common when authors deal with similar structures, since their origin is also similar and thus cannot be used as a basis for distinction. Below are a few examples of specific classifications.

Davies (1965) mentions (p. 309) that genetic classification is the best and most natural. He provides a morphologic classification of convolute lamination structures. This classification is summarized in Table III. It is clear that the author does not resort to the genetic factor.

Macar (1958) also uses a morphologic basis in classifying intraformational deformations. He groups them into three categories:

(1) folds, with a distinct discontinuity at the top, that become generally more pronounced from bottom to top;

(2) folds which suddenly stop above (but without a clear discontinuity) and below;

(3) folds which diminish gradually upwards and downwards (see Figure 13).

Each type has its distinct origin; however, this factor is not included in the classification, although Macar considers that mentioning the origin gives genetic value to the classification.

Kelling and Walton (1957) provide a descriptive classification of load casts. This classification is based on the position of structures in the upper or lower parts of strata. It is summarized in Table IV.

Anketell (1968) developed a purely morphologic classification of convolute laminations attributable to density. He thus identified a single origin, which for him eliminated the possibility of using origin as a parameter for distinction. He subdivides these structures into two groups according to their geometry: regular convection forms and forms resulting from discontinuities which do not penetrate the beds involved. Anketell (1970) expresses his dissatisfaction with the classification methods in use, including his own.

Finally, Wang (1983) classifies structures caused by the liquefaction of silts and sands in terms of their external form.

Few writers have used genetic classifications for limited groups of structures. One example is that of Elliott (1965), who developed a complex classification of deformation structures produced under water. He used the material behaviour (for example, quasi-liquid or hydroplastic) and kinematics as criteria. This classification clearly owes its complexity to the fact that, despite the restrictions on the field of application, a very large number of structural types are considered within it. This classification is given in Table V.

Macar (1958) also presented a genetic classification covering all phenomena resulting from differential vertical movement downward, all phenomena due to differential compaction, all deformations produced in a periglacial climate and so on. He encompasses a very large number of deformation structures in this classification.

Hayashi (1966) classified clastic dikes on the basis of several criteria - form, geometry, assembly, deformation and origin. He thus covers all possible elements in the classification of dikes; this is a disadvantage, since a classification that is so far-ranging is difficult to apply and becomes rather impractical.

This review of classification methods and the examples provided illustrate the complexity of the subject. On the one hand, everyone is trying to establish a precise classification based on the description of phenomena without reference to origin. This is difficult, since a number of terms used in naming deformation structures have a genetic connotation and their use gives a bias to classification systems.

On the other hand, several authors prefer a purely genetic classification, although this is also difficult because the causes of the structures are not precisely understood. In certain cases, there are contradictory suggestions about the causes of a given phenomenon.

CONCLUSION

In this chapter, we have reviewed various important aspects of the study of deformation structures.

We have shown that there is no consensus on the terms used in the literature to define structures, nor on the concepts denoted by such terms. There is some confusion in the usual application of names. It would be appropriate to try to correct this situation by proposing a terminology that is either purely descriptive or purely genetic. Such a task, for the most part, goes beyond the scope of this project and will not be dealt with here.

We have also briefly examined the nature of the physical agents known to cause deformation structures. This has been done in preparation for presentation of the general topic of structure classification. In this area as well, we find

there is no unanimity and that various authors suggest different systems, depending on their perception and understanding of the subject which, by all indications, is a very complex one.

MAIN DIVISIONS AND CHARACTERISTIC FEATURES OF THE CLASSES OF STRUCTURES

	Convolute lamination	*Corrugated lamination*	*Cusp structures*[1]
Morphology perpendicular to the bedding	a series of narrow anticlines and broad synclines	complex with no regularity	isolated anticlines
Morphology parallel to the bedding	variable: anticlines form variants between ridges and cones often with a sub-parallel arrangement	complex but sometimes a sub-parallel trend may be recognised	circular to ellipsoidal form most common
Vertical variation	restricted to one bed and dies out downwards and in some cases upwards with continuity of lamination	as for convolute lamination	normally deformation only affects one bed and dies out downwards with continuity of lamination
Lateral variation	often persistent over wide areas but exceptions do occur especially in non-turbidite environments	very variable in style	sporadic in occurrence

[1] Cusp structures have been included in this classification as they are very similar in some respects to convolute lamination.

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TABLE III - Classification of convolute laminations, from Davies (1965)

Upper-surface Structures	Under-surface Structures	
	Undeformed	Deformed (Flow-casts, Shrock, 1948 Load-casts, Kuenen, 1953)
Group I.		
A. *Grooves* (Drag-marks, Kuenen and Sander, 1956)	*Groove-casts* (Shrock, 1948)	*Groove-load-casts* (in part, torose load-casts, Crowell, 1955) (in part, Korkzieher Zapfen, Rücklin, 1938)
B. *Flutes* (Flow-markings, Rich,	*Flute-casts* (in part the flute-casts of Crowell, 1955) (Flachzapfen and in part Einfache Zapfen-wulste, Rücklin, 1938)	*Flute-load-casts* (Load-casts and in part flute-casts and torose load-casts, Crowell, 1955) (Flow-rolls, Rich, 1950) (Lobate rill-marks, Clarke, 1918) (Einfache Zapfen-wulste in part and Korkzeiher-Zapfen in part, Rücklin, 1938)
Group II.		
A. *Transverse Ripple-marks*	*T-Ripple-casts*	*T-Ripple-load-casts* (? Flow-casts, Prentice, 1956)
B. *Longitudinal Ripple-marks*	*L-Ripple-casts*	*L-Ripple-load-casts*
C. *Interference Ripple-marks*	*I-Ripple-casts*	*I-Ripple-load-cast*

TABLE IV - Classification of load casts, from Kelling and Walton (1957)

NATURE OF OPERATION / SEDIMENT BEHAVIOUR	Diagram not to scale	EXOKINEMATIC			ENDOKINEMATIC			BIOKINEMATIC
		Tranquil flow	Low-flow	High-flow	Translation Slumps	Transposition Horizontal	Transposition Vertical	
FLUIDS	Grain by grain building	Even bedding	Cross stratification					Simple, short, varied orientation
QUASI-LIQUID	Formation en masse, dissolution of previous structures			Roundel sand-waves	Graded bedding Slurried bedding	Clastic intrusions Auto-injection breccias	Sand volcanoes Stromaters	Life restricted, traces cannot be recorded
				Parting lineation Dendritic ridges				
HYDRO-PLASTIC	Deformation and moulding, may be teased or drawn out, no dislocation or dissolution		Erosion ripples Dimples	Frondescent marks and longitudinal furrows Tool marks 'Streaked-out ripples' Convolute bedding	Slurry-slump bedding	Corrugated bedding	Cusps Load mark and pouch structures Small diapiric folds	Surface traces of small animals
				Deformed cross-stratification		Crumpled bedding	Mud-lumps	
QUASI-SOLID	Dislocation with concordant fault wall surfaces; trace apart; slight bending is possible			'Planting' slabs	Slide-slump bedding	Shredded bedding	Gallleleites	Disturbance, contact-small
SOLID	Discordant fault walls, undeformed fault blocks; sharp erosion			'Pot holes'	Slide-bedding	'Jumbled block' structures		Clear-cut traces

TABLE V - Genetic classification of deformation structures formed under water (Elliott, 1965)

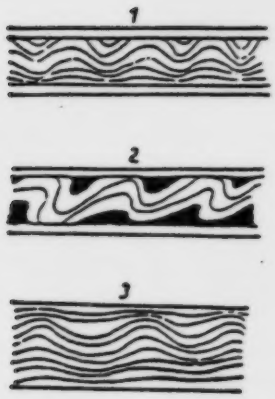

Figure 13 - The three main types of intraformational folds, after Macar (1958)

CHAPTER IV

ANALYSIS - SYNOPSIS

INTRODUCTION

In this chapter, we present the results of the analysis of texts acquired during the bibliographical research. Various aspects of the analysis will be described, all for the purpose of achieving the objective of this project.

WORK METHOD

As mentioned in Chapter II, the number of texts obtained was considerable and the extraction and use of relevant information was done using a coding system to prepare a computerized file. This file facilitated establishment of correlations between the elements noted in the texts through the use of sort functions employing codes. This system has already been described (Chapter II).

RESULTS

The results of the analysis concern several aspects, of which certain ones are only slightly relevant to the purpose of the project, which is to define criteria allowing identification of deformation structures caused by seismic activity. However, some of these results are helpful in understanding the context of the subject and we shall present them here.

1 - Number of publications per year by subject

Table VI shows the total number of publications recorded on the subject of deformation structures, in terms of an average for each five-year period. It will be seen that publications were few in number for the years up to 1935. From then on, the number increased at a consistent rate until 1950, and from that moment it has increased substantially up to the present. This growth curve seems to correspond to the increase in the number of publications in all areas of geology and does not warrant any conclusion about a sudden awakening of interest in deformation structures.

On the other hand, the number of publications on structures in which earthquakes are mentioned (indicated by the dashed lines) has increased since 1965 and since 1975 has comprised a large fraction of the total number of publications. We believe this reflects the impact of the 1964 earthquake in Alaska. That earthquake caused deformations of various types, arousing the interest of researchers concerned by earthquake prediction. The curve of publications referring to earthquakes is stable from 1900 to 1965, with few articles on the subject. It nevertheless indicates that several writers had long associated these structures with earthquakes.

2 - Types of structures and causes

Table VII presents an overall summary view of the results of the bibliographical research. The types of structure are given along the vertical axis, while causes of structures identified by writers are given in percentage along the horizontal axis. We see, for example, that convolute laminations are considered by 32% of all authors to be caused by gravity.

On the far right of the table, the percentage of publications dealing with a specific topic is given in the vertical column. Finally, the relative importance of each cause identified is expressed in percentage horizontally along the bottom of the table.

The major points indicated by this table are given below.

(a) - Causes - According to the authors of the texts analysed, all types of deformation may be attributed to more than one cause. Of these, earthquakes are identified in the literature as the most frequent cause of deformations (32%). This is especially true for recent years and is only the reflection of the interest noted above. The effects of gravity are next, with 24%, while other causes (density, waves and currents, glacial and periglacial effects) follow with figures of similar magnitude varying from 11 to 14%. These values are valid for the bibliographical research done under this project and cannot be taken as a faithful representation of reality because of the inherent bias of the work. However, they are indicative.

As a cause, earthquakes are linked to 72% of faults and fractures, 69% of clastic dikes, 65% of slumping and 64% of sand and mud volcanoes. This is only an association of ideas and the table must not be interpreted in terms of a precise relationship of cause and effect. The values in the table are influenced by the interest shown in earthquake effects since 1964, as mentioned earlier, and represent only the results of the bibliographical research done.

(b) - Deformation structures - Not all deformation structures attract the interest of researchers to the same extent. For example, 34% of the publications concern convolute laminations, while the figure is 21% for clastic dikes (8% with filling from above and 13% with filling from below), 10% for load casts, 9% for slump structures, 7% for ice wedges and frozen-ground effects, and lower, more or less identical percentages for the other types of structures (ball-and-pillow, pseudonodules, sand and mud volcanoes, faults and fractures).

This distribution seems to reflect the corresponding natural frequency of each type of structure and the interest it evokes.

3 - Causes of deformation structures

Table VII contains useful information on the causes of deformations; however, for a better understanding of their significance, the causes proposed for each type of structure should be examined in detail. We will now do this to determine which structures are clearly caused by earthquakes. This is the first stage in establishing criteria.

Before we look at the causes of each structures, as revealed by analysis of the documentation, two precautions are appropriate.

1 - The conclusions drawn by the various authors about various causes do not all have the same degree of credibility. Some conclusions are more justified than others and deserve more attention. This is the result of the line of reasoning followed by each author in arriving at his conclusions. During the analysis of the data sheets, we recognized three distinct processes:

- conclusions based on direct observations (often visual);

- conclusions based on the results of laboratory experiments;

- conclusions based on the analysis of indirect geological indications.

TABLE VI - Number of publications per year
(five-year averages)

Total publications
Publications mentioning earthquakes

PUBLICATIONS

YEAR

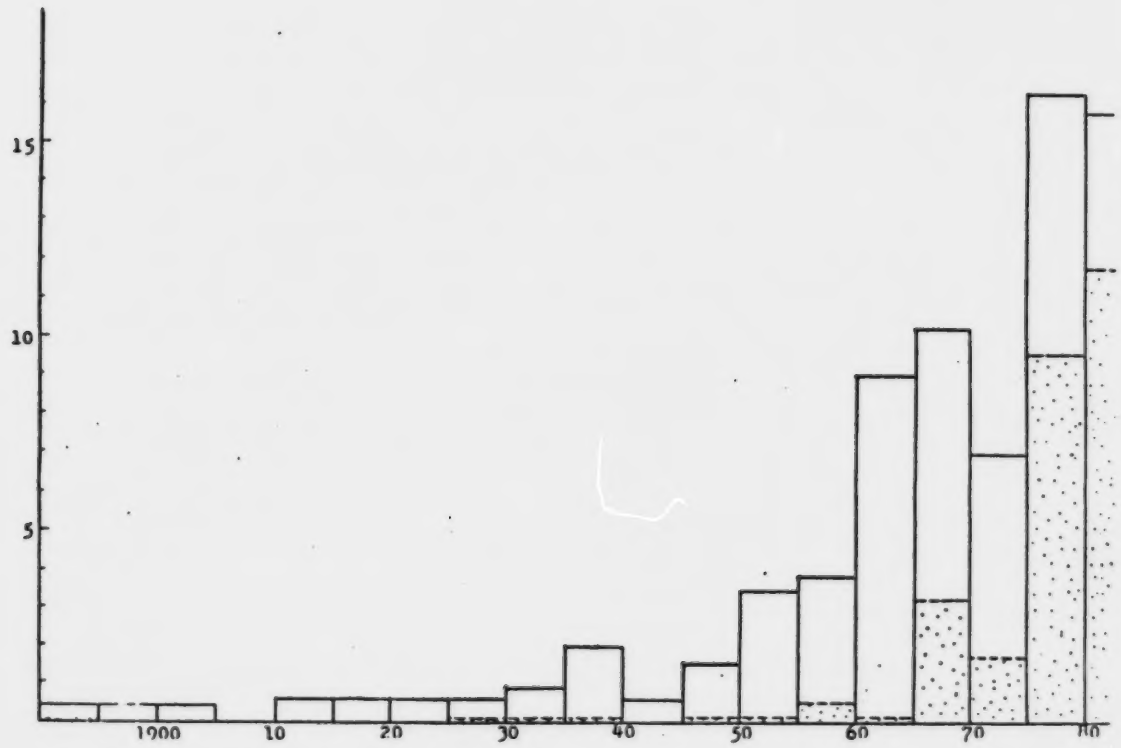

TABLE VII

TYPES OF DEFORMATION STRUCTURES VS CAUSES

(expressed in % of references made)

TYPE	GRAVITY (COMPACTION/ SLIDING	DENSITY	CURRENT/ WAVES	GLACIAL/ PERI-GLACIAL	TECTONIC	EARTH-QUAKE	OTHER	TOTAL
	%	%	%	%	%	%	%	%
LOAD CASTS	14	43	17	9	0	17	0	10
BALL-AND-PILLOW STRUCTURES	46	8	15	0	0	31	0	4
PSEUDONODULES	46	8	8	0	0	38	0	4
CONVOLUTE LAMINATIONS	32	13	24	18	0	13	0	34
SLUMP STRUCTURES	26	0	3	0	0	65	6	9
CLASTIC DIKES filling from above	35	0	19	15	19	12	0	8
CLASTIC DIKES filling from below	14	9	0	0	16	57	4	13
SAND VOLCANOES	14	4	0	0	4	64	14	6
ICE WEDGES/ FROZEN-GROUND STRUCTURES	12	0	8	80	0	0	0	7
FAULTS/FRACTURES	17	0	0	5	6	72	0	5
TOTAL %	24	11	13	14	4	32	2	100

Each of these paths of logic corresponds to a different degree of realism and the conclusions reached do not all have the same value in establishing the probability of the causes.

- Conclusions based on direct observations

Direct observation of deformation structures as they form during the occurrence of a natural phenomenon provides the most reliable evidence about the nature of causes and have the greatest degree of credibility.

For example, several articles mention the testimony of people who have observed sand or mud volcanoes in action during earthquakes.

Following seismic activity, witnesses and researchers have observed material injection phenomena (clastic dikes) in the walls of observation trenches. These observations leave no doubt and provide indisputable proof of how a number of deformation types occur.

A high credibility rating must also be given to observations made soon after the occurrence of a phenomenon, although not during it, if no other disturbing agent has acted in the meantime. Coleman (1969), for example, studied the deposits resulting from a recent flood in Pakistan. Some deposits were deformed and the deformations have been attributed to current effects; this is plausible, since no other agent besides gravity and the current could have been involved.

In the same way, Coleman et al (1964) studies the alluvial deposits of the Mississippi River and observed structures which they attributed to the current. A final example is that of Sikirdji (1982), who studied the deposits observed behind a dam after the reservoir was emptied. These deposits, which were less than 45 years old, had been affected only by the current. In such cases, the cause of a structure is easy to identify and hard to doubt.

- Conclusions based on the results of laboratory experiments

There have been many laboratory experiments on the original of deformation structures. In such cases, the cause is chosen and applied, and the conclusion establishing the cause and effect relationship is just as valid as that derived from direct observation. However, the act of isolating agents eliminates interactions found in nature and the cause and effect relationship established is not exclusive. In fact, the structure observed can also be formed by the action of other factors not involved in the experiment. Moreover, it is difficult in any experiment to completely isolate a cause. In most cases, several agents are at work and its is difficult to determine their relative contributions to the process observed. This will be discussed in greater detail in the evaluation of causes.

- Conclusions based on the analysis of indirect geological indications

This type of conclusion is the most common and has the lowest credibility rating. It is the basis for most discussions concerning the origin of deformation structures. About 80% of the texts analysed describe and discuss structures produced in materials that are between Quaternary and Precambrian

in age and are often lithified. Structures are interpreted only by means of incomplete indications which do not allow the distinction of a single cause. When a writer identifies a single cause, he often does so from imprecise indications. Credibility is at its lowest level, and this explains the polemics and speculation surrounding discussions on causes. For example, a number of authors (Butrym et al, 1964; Dzulynski, 1965; Halicki, 1960) reach the point of questioning the origin of structures attributed to glacial or periglacial effects. In their opinion, these deformations may sometimes be caused in the absence of ice or cold.

The conclusion we may derive from this cautionary note is that it is helpful to specify the nature of the observations made in discussions of causes.

2 - The second note of caution concerns an effect commonly found during analyses of the literature. It is often apparent in such cases that several authors are greatly influenced by the writings of another person, whom they cite and whose conclusions they adopt from the start. The publication by Kuenen (1953) of the results of his laboratory experiments on the formation of convolute laminations, load casts and pseudonodules oriented the conclusions of many authors (Holland 1959; Weaver, 1976), who describe similar structures formed in a natural context. Several of them adopt his conclusions on the causes without really discussing them. Others quote authors who used Kuenen's conclusions, resulting in a "snowball" effect that leads to a distortion of the values shown in Table VII. This reinforcing effect is also apparent where direct observations of a natural phenomenon are concerned. Judgement must therefore be exercised in analysing figures for the frequency of causes cited for a given structure, since they may easily be biased. Moreover, in preparing Table VII, we have not included opinions that have been repeated either by an author who deals with the same subject in several articles or by writers who state that they have been directly influenced by the opinion of another person. This mitigates the reinforcing effect, while not eliminating it.

LOAD CASTS

According to Table VII, load casts are caused by at least five well-identified agents. Forty-three per cent of the authors attribute these structures to effects of density contrasts between two beds. Of these, we should mention Collinson and Thompson (1982), Dylik (1961), Kaye et al (1954), Kelling and Walton (1957), Kuenen (1953), Middleton and Hampton (1973) and Dzulynski and Walton (1963). Only Dzulynski and Walton (1963) base their conclusions on experimental data. All the others derive their conclusions on experimental data. All the others derive their conclusions from indirect observations (in other words, geological indications). None uses the evidence of direct observation.

Seventeen per cent of the writers believe that load structures result from current action. Kuenen (1953) and Prentice (1960), among others, suggest this hypothesis. Fourteen per cent attribute these structures to the effect of gravity. These include Arogyaswamy (1962), Baker (1973), Allen (1970), Dzulynski et al (1962), Kaye (1954) and Kuenen (1953). Kuenen's name is often mentioned because he has proposed several hypotheses.

Seventeen per cent attribute these structures to earthquakes. Sims (1973) observed these structures after the San Fernando earthquake in 1971 in the sediments deposited behind the Van Norman dam. This was direct observation. Kuenen (1958), moreover, attributed the formation of such structures to the effect of an earthquake, after analysing the results of experimental studies. The earthquake, in his opinion, caused the breakage of a soft, saturated layer which became liquefied, allowing the denser overlying material to sink into it under the effect of gravity. According to his explanation, the earthquake acted as a trigger and is the immediate cause, although not the main one, of load casts. Collinson and Thompson (1982) and Gubler (1966) mention this possibility. Lamar et al (1979), Munoz et al (1977) and Weaver (1976) also suggest earthquakes as a cause.

Finally, nine per cent of the writers are of the opinion that these structures result from glacial or periglacial forces.

These differing conclusions, apparently well-founded, illustrate the problem in determining causes. Anketell et al (1970) summarized the situation as follows: [original English] "Deformations genetically diverse [sic] may be morphologically indistinguishable" (p. 25).

Since structures having different origins resemble each other to such an extent that their characteristics do not allow us to determine their cause, as is the case for load casts, we have no choice but to disregard this kind of structure in the search for criteria of seismic activity. Indeed, no author has discovered features that are unique to structures caused by earthquakes.

BALL-AND-PILLOW STRUCTURES

This type of structure is rather rate and few writers have shown an interest in it. Only thirteen of the chosen texts deal with this kind of structure. Of this number, about half of the authors (46%) are of the opinion that they are gravitational effects, and 8% add to this the effect of contrasts in density. Allen (1970) thinks that ball-and-pillow structures result from gravitational instability prior to lithification. Button (1977), Conybeare and Crook (1968) and Potter and Pettijohn (1963) have more or less identical opinions. On the other hand, a few writers evoke density in addition to gravity. Benson (1980) and Leeder (1982) hold this view. Fifteen per cent of the authors suggest current action as a formation mechanism. Dzulynski and Randomski (1966), moreover, have created these structures experimentally using only currents simulating turbidity currents. Finally, 31% of the writers suggest seismic shock as a mechanism that triggers the liquefaction of a bed in which balls and pillows sink. Howard et al (1969), Middlemost (1967), Potter and Pettijohn (1963) and Weaver and Jeffcoat (1978) propose such a mechanism.

In this case, as for that of load casts, earthquakes may act to initiate or trigger the phenomenon, which then proceeds in accordance with a completely different mechanism. The final result reflects this mechanism and not the earthquake. Therefore, the consequent structure cannot provide earthquake criteria. In addition, since ball-and-pillow structures can occur without the action of earthquakes, in the opinion of some authors (Benson, 1980; Allen, 1970; Dzulynski et al, 1966), their occurrence does not automatically imply seismic activity. This type of structure can thus not be used for purposes of this study.

PSEUDONODULES

This type of structure is not commonly observed and only thirteen authors have dealt with it. Forty-six per cent considered these structures to have been formed under the effect of gravity alone, while 8% think that density contrasts have been added to the effect of gravity. Blatt et al (1972), Gubler (1966) and Macar (1948) believe these structures are the result of the vertical or quasi-vertical downward movement of a sense material into a less dense material that is in a hydroplastic state. Dionne (1971) suggests the action of differential stresses. Dzulynski and Radomski (1966) explain such structures by the action of fast currents carrying heavy sediment loads. Their opinion is the result of experiments which reproduced the structures.

Finally, 38% of the writers suggest earthquakes as an important agent. Sims (1973), 1979) has observed similar structures behind the Van Norman dam in California. He attributes the formation of pseudonodules to the 1971 San Fernando earthquake. In his opinion, the pseudonodules observed are identical to those produced experimentally by Kuenen (1958). Kuenen (1958 and 1965) describes the results of experiments on a model and identifies pseudonodules created by gravity following a shock. Again, a shock only triggers the phenomenon. Hayashi (1970) and Macar (1948) have a similar view.

It seems certain, according to visual observation and experiments on a model, that seismic activity can lead to conditions which favour the formation of pseudonodules. One of these conditions is liquefaction of the layer into which the material forming the pseudonodules sinks. However, according to Dzulynski and Radomski (1966), earthquakes are not required; in fact, they managed to produced pseudonodules without the use of shocks.

Since this kind of structure is formed by a process that is distinct from that which triggers it, it does not provide any characteristics that are peculiar to earthquakes and cannot be used for our study.

CONVOLUTE LAMINATIONS

This type of structure is the most commonly referred to in the literature. No fewer than 119 authors, or 34% of the authors of all the texts catalogued, have dealt with this subject. As defined earlier, this structure type includes strata folded in the form of convolutions or involutions, with folds of low to high amplitude, both complete and truncated. The only fold structures not included in this category are those designated as frozen-ground structures, and these are often similar. They will be examined later.

Thirty-two per cent of the authors attribute convolute laminations to the effects of gravity, associating them with slumping. Some have observed them directly soon after their formation. Bigarella et al (1969), for example, have seen them in sand dunes in Brazil and ascribe them to the force of gravity acting on material deposited in steeply dipping beds. Coleman et al (1964) describe such structures in the deltaic deposits of the Mississippi and attribute them partly to slumping. McKee (1938) has examined them in sediments formed during floodings of the Grand Canyon of the Colorado; he also puts them down to slumping. These direct observations clearly indicate that convolute laminations can be formed under the effect of gravity. This is

confirmed by the results of laboratory experiments on reduced models. McKee (1964), Nagtegaal (1963), Anketell et all (1960), Rettger (1935), Allen (1977) and Deely (1916) concluded as a result of such work that gravity was an important factor in creating these structures, with the help of other agents in some cases. Several writers have come to these conclusions after analyses of indirect geological indications. (Bretz (1913), Conybeare and Crrok (1968), Fairbridge (1947), Jardome (1965), Kato (1979), Kent (1945), Kirsch (1950), Okko (1967), McArthur et al (1970), Tada (1968), Nagtegaal (1963), Rice (1939), Selley et al (1963), Shaw (1977), Smith (1959) and Straaten (1949) are examples.

In spite of this impressive list of writers who have concluded that gravity is a cause of these structures, several have differing opinions. Twenty-four per cent of the authors attribute such structures to the effects of current and waves. Direct visual observations support this opinion. Coleman (1969) observed convolute laminations in the delta of a river and attributed them to the effect of current alonge. He repeats this view in a number of articles: Coleman and Gaglinano (1965), Coleman et al (1964). McKee (1964) and McKee et al (1967) agree, but add the combined effect of gravity.

Sikirdji (1982) examined convolute laminations in the upper part of beds deposited behind a dam in a reservoir that had just been emptied. Because of the position of the structures, he eliminated gravity and density effects as causes, retaining only the effects of current. In addition to these direct observations, a few authors have reproduced convolute laminations experimentally, using currents. McKee (1964), Nagtegaal (1963), Dzulynski (1965), Anketell (1970), Selley (1969), McKee et al (1971) and Kindle (1917) all succeeded in producing varied but similar convolutions by means of currents. Finally, several authors found that currents were effective as a cause of the structures observed in sedimentary rocks and in old and recent sediments. Examples are Blatt et al (1972), Crowell et al (1966, Ghent et al (1965), Gubler (1966), Heaaf (1956), Holland (1959), Kato (1979), Kuenen (1953), Dott and Horward (1962), Rice (1939), Sanders (1960), Stewart (1962) and Allen and Bank (1972). According to these observations, therefore, it is assumed that currents acting on saturated beds, usually in a hydroplastic state, can cause convolute laminations of various types.

Thirteen per cent of the authors attribute convolute laminations to the effects of density; in other words, they result from contrasts in density. Since this mechanism is difficult to observe directly, no visual evidence has been used in support of it. From an experimental point of view, Deely (1916) belives that convolute laminations are the result of the sinking of a high-density matieral into another material of less density. Anketell et al (1970), after experiments which led to the production of convolute laminations. They used shock trigger the formation process. Finally, a few authors suggest the possibility of liquefaction of a bed during an earthquake to start the process. Collinson and Thompson (1982), Henderson (1935), Holland (1959), Jardine (1965), Jones (1962), Rascoe (1975), Russ (1979) and Allen and Banks (1972) are examples.

Finally, one author suggests the hypothesis that these deformations are the result of the pressure of air trapped in sediments. Stewart (1956) observed convolutions being formed in modern sediments in a lagoon. Moreover, he reproduced this phenomenon in the laboratory. This formation mechanism is therefore undeniable.

It is clear from the foregoing that convolute laminations can result from various causes acting separately or, sometimes, simultaneously. Visual observations, supported by laboratory experiments, and geological observations demonstrate this.

Davies (1965) has summarized the available information in a table, which we have reproduced (see Table VIII); it shows that different formation processes have occurred at various stages of diagenesis.

The practical conclusion to be drawn from these considerations is that convolute laminations cannot provide criteria characteristic of earthquake activity as a mechanism of formation.

SLUMP STRUCTURES

Slump structures are those which can be formed during the slipping or displacement of materials, on a small or large scale, on the surface of the ground or under water. Slumping may involve simply the displacement of one bed over another along an inclined plane, or the movement en masse of great thicknesses of sediments over large distances and at high speeds. These structures thus occur on various scales of size, from the smallest to the largest. Before summarizing the information taken from the literature, we must mention that gravity, by definition, is the force behind slumping. It is therefore superflous to identify this as the only cause of slumping, as 26% of the authors consulted have done.

PUBLISHED HYPOTHESES ON THE FORMATION OF CONVOLUTE LAMINATION

Author and year	*Time of formation*	*Mode of formation*
KUENEN (1953b) TEN HAAF (1956)	syndepositional	plastic deformation of ripple marks coupled with loading phenomena
SANDERS (1960)		deformation of cohesive sediment in response to shearing effects set up high velocity currents
DZULYNSKI and SMITH (1963)		(*a*) current deformation of a plastic sediment (*b*) loading pressures
SELLEY et al. (1963)	metadepositional	quick sand movement aided by upward migration of interstitial water
STEWART (1956)		deformation due to upwelling of trapped air pockets within a sediment below water level
DUTT and HOWARD (1962) NAGTEGAAL (1963)		gravity induced false body thixotropic sediment behaviour
RICH (1950)	postdepositional	sliding of overlying sediment deforming a bed by shearing forces
WILLIAMS (1960)		intrastratal laminar flow

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TABLE VIII - Hypotheses concerning the origin of convolute Laminations, from Davies (1965)

Sixty-five per cent of the authors establish a direct link between eartquakes and slumping, in many cases as a result of direct observation during and after an earthquake. The 1964 earthquake in Alaska caused major slumping over a large part of the area affected. In that case, slumping was clearly related to the earthquake. Coulter and Migliaccio (1966), Reinmitz and Marshall (1965 and 1972) and Tuthill and Laird (1966) have described slumping caused by this earthquake, both on land and on the sea floor. In addition, Seed (1968) provides quite a long list of slump structures that can be ascribed to earthquakes. Finally, many writers have suggested earthquakes as a cause on the basis of indirect observations. Andresen and Bjerrum (1967), Bailey and Weir (1932), Dott (1963), Gregory (1969), Mikulenko (1967), Molnia et al (1977), Nichols (1960), Qamar and Kogan (1981) and Verzilin (1961) are examples.

A small percentage (3) of the authors have turned to other causes, such as currents, waves, gas in the sediments and frozen-ground structures. In all such cases, the conclusions are not based on direct or experimental observations.

Slump structures, therefore, are often triggered by earthquakes, generally through liquefaction of saturated silty beds. The movement following liquefaction is the result of the force of gravity and the final product of the movement provides no distinctive sign that can link it to the earthquake. At least, no author has observed or described any such sign. Therefore, this type of structure cannot be used in establishing the criteria we are seeking.

CLASTIC DIKES

This type of structure has been described in Chapter III. The analysis of the literature indicates that clastic dikes are common and that 21% of the authors have mentioned them. This kind of structure is second to convolute laminations in the number of times it has been referred to, and the first texts describing them date from 1890. The analysis of available texts points to a major distinction made by several authors in covering the subject. This distinction concerns the direction from which dikes are filled, either from the bottom upward or from the top downward. The distinction is an important one, since it implies different origins in almost all cases. We will retain this distinction and our treatment of dikes will deal with each element.

A - Clastic dikes filled from above - Eight per cent of the texts obtained deal with this subject. Of these, 35% take the view that dikes are fissures of various origin (tectonism, desiccation and so on) filled by gravitational action. In other words, particles are deposited in the fissures by force of gravity alone. No direct observation or experiment supports this conclusion. The only indications are indirect geological ones. Bump (1951), mentions that clastic dikes in Oligocene sediments of [South] Dakota are the result of the filling from above of desiccation cracks. Case (1895) expresses an almost identical opinion about fissures filled from above. Glennie (1970), Lawler (1923), Vitanage (1954) and Yanushevich (1972) describe similar cases.

Nineteeen per cent of the writers ascribe the filling action to currents (Dionne and Shilts, 1974; Lupher, 1944), while the same proportion attributes them to regional tectonic phenomena. Fifteen per cent put them down to glacial or periglacial effects (Dionne et al, 1974; Elson, 1975). Finally, 12% relate them to earthquakes (Dzulynski et al, 1956; Neruchev, 1959).

The diversity of origin and the lack of direct observation concerning origin mean that this type of structure cannot be used for purposes of our project.

B - Clastic dikes filled from below - Dikes filled from the bottom up are the result of a mechanism which must work against gravity and must therefore have energy to fill the fissures by an injection process.

Fifty-seven per cent of the authors attribute these dikes to earthquake action. Many visual observations confirm this conclusion. Coleman (1969) mentions that several people were witnesses to the formation of clastic dikes during an earthquake in 1935. Coulter and Migliaccio (1966) and Reinmitz and Marshall (1965) write that people saw ridges of sand on the surface of the ground soon after the 1964 earthquake in Alaska. These ridges, which were not there before the earthquake, are the surface manifestation of clastic dikes formed during the earthquake. Finally, Wang (1981) refers to the presence of dikes observed in trenches soon after the Tangshan, China earthquake of 1976. These observations constitute undeniable confirmation of clastic dike formation through filling from the bottom as a result of seismic activity. There is no experimental study on a model to support these visual observations. On the other hand, there are many writers who explain the "seismic" formation of dikes from geological observations. Andrieux (1967) indicates that these dikes are the result of a sudden, rapid process, such as an earthquake. Bailey (1932), Blatt et al (1972), Coric and Manovlic (1981), Collinson and Thompson (1982), Damberger (1973), Diller (1890), Cuncan (1964), Dzulynski et al (1956), Hayashi (1966), Henderson (1935), Hesse (1976), Lambrecht et al (1966), Laming (1966), Marshalko (1972), McCallis (1903), Russ (1979), Verzilin (1961) and Waterstone (1950) adopt this explanation for clastic dikes of all sizes observed in very old rocks, as well as in recent sediments. Their conclusions are generally based on indications such as the internal parallelism of injected particles, the regularity of the walls, the granulometry of the injected material, the dragging of blocks that have come from the walls of the intruded rock and so on. Many indications confirm that clastic dikes are sometimes the result of earthquakes.

Sixteen per cent of the authors relate dikes injected from below to regional tectonic activity. Allison (1953), Beutner (1978), Gottis (1953), Harms (1965), Peterson (1966), Russel (1927), Smith (1952) and Zupan and Abbott (1975) use this explanation for the origin of dikes generally observed in very old rocks. A number of writers have been able to establish a relationship between the orientation of the dikes and that of regional stresses. None gives the specific mechanism related to the tectonic stresses. Fourteen per cent attribute the dikes to gravitational effects. No direct observation or experiment confirms this hypothesis. Arogyaswamy (1965) suggests synsedimentary slipping with injection of dikes along the rupture planes under the weight of the displaced material. Jenkins (1925) mentions gravitational filling of open fractures. The filling would be by injection from below. Smith and Rast (1958) refer to "slumping" of rock masses with injections along fracture planes. Finally, a few authors relate these dikes to the effects of density, glacial or periglacial phenomena, or hydrostatic pressure (which resembles the result of liquefaction by earthquakes). None of these mechanisms has been observed or reproduced experimentally.

Most of the more convincing indications suggest that earthquakes are a major cause of the formation of clastic dikes filled from below, probably by injection, especially where recent phenomena are concerned. Accordingly, this type of structure is worth considering in the establishment of seismic activity criteria.

SAND AND MUD VOLCANOES

This kind of structure is not very common, since it is rarely preserved intact and observed in rocks. Only 6% of the authors dealt with this subject, and most of their observations concern current or recent occurrences.

Sixty-four per cent of the writers attribute sand and mud volcanoes to seismic activity. Several record the testimony of people who have seen them being formed or activated during earthquakes. Coleman (1969) refers to visual observations of sand volcanoes in action during an earthquake in 1935. Coulter and Migliaccio (1966), Reinmitz and Marshall (1965) and Tuthill and Laird (1966) mention the observation of many mud spurts during the Alaska earthquake in 1964. Jaime et al (1981) describe the action of volcanoes observed before the end of an earthquake in Mexico in 1979. Oldham (1872) reports a similar observations during an earthquake in India in 1969. Talaganov et al (1891) made an identical observation. Rascoe (1975) gives an account of several visual observations of sand volcanoes in action during earthquakes (1811-1812), New Madrid; 1906, San Francisco; 1933, Long Beach, 1959, Yellowstone; 1973, California). Ambraseys (1969) provides a similar list (1897, Assam; 1928, Bulgaria; 1930, Dhubri, India; 1964, Niigata, Japan). Finally, Wang (1981) and Want et al (1983) mention the formation of sand volcanoes during the 1976 earthquake at Tangshan, China. According to these writers, sand volcanoes are the result of liquefaction of a deep sandy layer, with expulsion of water and sand at the surface through the underlying layers, which break because they are not supported by the liquefied layer. The phenomenon has been reproduced in the laboratory only by Weaver and Jeffcoat (1978), using vibrations, and only a few authors mention it as a result of indirect observations: for example, Blatt et al (1972), Leeder (1982), Montenat (1980) and Sieh (1978). Collinson and Thompson (1982) add that these structures are frequently observed in association with clastic dikes.

Fourteen per cent of the authors attribute sand and mud volcanoes to gravitational force, without the influence of earthquakes. A few have observed sand or mud volcanoes formed in this way. Dionne (1976) observed similar forms in the strand zones of James Bay and attributed them to an overload from the weight of overlying sediments. Evans (1965) describes "mud pits" formed by the escape of gas at the surface resulting from an overloading effect. Sikirdji (1982) records a similar observation in recent sediments exposed when a reservoir was emptied. He also ascribes them to he release of gas under the effect of gravity. Burne (1980) has reproduced sand volcanoes experimentally. Gill and Kuenen (1958) have also observed similar forms in slumped sediments during experiments that simulated slumping. Water extrusion was the apparent cause.

These visual observations indicate clearly that sand and mud volcanoes can be formed in different ways. Volcanoes formed during earthquakes are generally of sand; in other words, sand from a lower bed is expelled at the surface

through a chimney. This type of structure is often preserved. On the other hand, volcanoes formed by the release of gas or the escape of mud under the force of gravity usually do not have a full central passage and are subject to collapse. They are rarely preserved.

Since this kind of structure is so directly associated with earthquakes by several authors, it will be used in establishing criteria of seismic activity.

ICE WEDGES - FROZEN-GROUND STRUCTURES

By definition, these structures are caused by frost and are glacial or periglacial phenomena. Ice wedges and frozen-ground structures are described in Chapter III.

Seven per cent of the authors of the texts listed discuss these structures and, as should be expected, 80% of these attribute such structures to frost. Few writers describe these structures as observed during formation, although a number of them have observed them under conditions in which the effect of frost is clear. Berthelsen (1979) describes folds and boudinage in Quaternay sediments and ascribes them to the force of gravity under frost conditions. Carruthers (1939) describes several types of structures caused by frost. Denny (1936), Dionne (1966, 1970 and 1975), Collinson and Thompson (1982), Dylik (1961), Gangloff (1970), Gubler (1966), Horberg (1951), Johnsson (1959, Konigsson et al (1977), Michel (1975), Sharp (1942) and Virkkala (1959) describe structures which they attribute to frost on the basis of geological observations. Lachenbruch (1962) produced models of ice wedges and polygon ground by means of freeze-thaw cycles.

There is no doubt that these structures are caused by frost. However, a few authors claim that frost is not required to form structures like these.

> [ORIGINAL ENGLISH] The present paper is in line with this trend of investigations and aims to prove that nearly all of the described "periglacial structures" may easily be explained in terms such as load deformations, clastic dykes, spontaneous liquefaction, slumping, etc.
>
> Butrym et al (1964), p. 2

After experimental studies, Butrym et al (1964) concluded that glacial structures could be produced without frost action. Dzulynski (1965) demonstrated the same thing when he made "ice wedges" in the laboratory without frost action, using only the growth of diapirs. Several authors are aware of the possibility that structures identical to frost structures can occur. Dionne (1971) discusses the origin of some structural types (convolute folds, involutions, injection, pseudonodules and so on) in terms of differential loading and underwater slumping, even though they are observed in sediments deposited under periglacial conditions. Halicki (1960) warns against attributing all structures to frost action. He notes that several of these strongly resemble structures formed by other mechanisms. Moerner (1982) goes further, writing:

> [ORIGINAL ENGLISH] Similarly "glacial deformed bedrock: and many "deformational tills" are likely to represent paleoseismic events (rather than glacial activity).

This opinion is not entirely supported by the author, but it does indicate the approach taken by a number of researchers.

We should keep in mind from all this that structures such as ice wedges and frozen-ground phenomena are the product of glacial or periglacial phenomena, but that identical or very similar structures can be the result of other causes, even in regions where frost conditions once prevailed. We thus cannot automatically ascribe the cause of these structures to frost simply because they are observed in locations where frost did prevail when the structures were formed.

A problem related to the diversity of origins concerns the resemblance of structures. Where ice wedges are concerned, certain criteria can be identified to distinguish them from similar structures resulting from other causes (such as clastic dikes). Collinson and Thompson (1982) mention that ice wedges have a rather well-defined conical cross-section with narrowing toward the bottom and a complex process of filling, with several phases of varied lithology distributed in zones parallel to the walls of the fissures. The fill material differs from that of the invaded sediment. Elongate fragments sometimes have a preferred orientation (with the longest axis parallel to the walls of the fissure). However, these criteria, except perhaps the first one, are not unique to ice wedges, and cannot be confused with clastic dike forms; this is of some importance for our study, since we have selected clastic dikes for the purpose of establishing criteria.

Finally, frozen-ground structures resemble convolute laminations; in some cases, the origin cannot be distinguished by means of criteria. Since these structures are not being chosen for purposes of the project, this probable confusion is of no consequence.

We should add that the study of structures caused by ice is a complex field. Coates (1975) has provided a survey of deformations attributable to ice. This review covers interesting aspects, such as the complexity of glacial deposits, the glacial mechanisms which deform sediments, with a classification of these, and a classification and description of the characteristics of the deformed sediments. Interested readers are referred to the text by Coates (1975).

FAULTS - FRACTURES

This type of structure is often mentioned in association with other deformation structures. We have included it here because some authors refer to it as a site of seismic activity. On the other hand, these structures can result from several causes and occur in various forms, most of which are attributable to regional tectonic activity.

No one suggests that earthquakes are the direct cause of faults and fractures, so we will not dwell on the subject. These structures are not relevant for purposes of our work.

SIZE AND ORIENTATION OF DEFORMATION STRUCTURES

All information from each article concerning the size and orientation of structures was compiled to determine, if possible, dimensional and geometric characteristics which could be used as criteria in identifying the origin of certain types of deformations.

The main obstacle in achieving this objective was that researchers are not very interested in taking size measurements. In most texts, no mention is made of dimension or general orientation of structures. On these points, descriptions are often incomplete and the only useful indication at times is the presence of a pencil, compass or coin in a photograph, or of a scale on a drawing. The reason for this neglect is probably the variability in size of each deformation type, not only from place to place, but also at a given location. For example, there is often a short note mentioning that size varies from a few centimetres to a few metres.

The results of the compilation are summaried in Table IX. The data, which is abundant in spite of everything, does not say very much unless it is examined with the help of such a summary. It will therefore be useful to look at certain types of deformation structure in greater detail.

(a) Convolute laminations. This type of deformation is referred to most often and also demonstrates the greatest variation in size. Moreover, it has the largest number of causes ascribed to it. Generally speaking, convolute laminations caused by currents, gravity, density or earthquakes are small in size - a few centimetres - and are found mostly in beds of sand and silt. No dimensional or geometric characteristic enables us to distinguish convolute laminations resulting from earthquakes from those having other origins. Convolute laminations formed by glacial or periglacial phenomena are sometimes large and involve various types of materials.

TABLE IX

DIMENSIONS OF DEFORMATION STRUCTURES

TYPE OF DEFORMATION	DIMENSIONS cm HEIGHT	WIDTH	ORIENTATION	MATERIAL	ORIGIN
LOAD CASTS	1-30	4-30	sometimes perpendicular to current	sand - silt or clay	density - current
BALL-AND-PILLOW STRUCTURES	60-300	60-400	parallel to beds	sand on silt or clay	density - earthquakes
PSEUDO-NODULES	5-10	10-150	--	sand - silt	density - earthquakes
CONVOLUTE LAMINATIONS	99 cm-+10 m	99 cm-+99 m	irregular - or perpendicular to current	sand - silt till	gravity - ice - current - earthquakes
SLUMP STRUCTURES	99 cm-+100 m	99 cm-+100 m	perpendicular to slopes	sand - silt	gravity - earthquakes

CLASTIC DIKES FILLED FROM ABOVE	5-500	5-500	vertical or almost vertical	sand - gravel -	glacial
CLASTIC DIKES FILLED FROM BELOW	1-+100 m	1-+35 m	following perpendicular or irregular joints	sand - silt clay	earthquakes
SAND VOLCANOES	2-40	40-400	--	silt - clay (mud) sand	compaction deaeration earthquakes
ICE WEDGES - FROZEN-GROUND STRUCTURES	2-1000	20-1000	--	clay - silt sand - gravel - till	frost - thaw (peri-glacial)

(b) Ice wedges - frozen-ground structures. These structures, classified together genetically, sometimes resemble other types of structures (indicated in this report under a descriptive classification, such as convolute laminations). They are characterized by wide variation in size (from a few centimetres to more than ten metres), the frequent occurrence of large sizes and the variation in nature of materials affected by them. Glacial and periglacial phenomena occur equally well in any unconsolidated material and seem to be independent of lithology. This is perhaps their most distinctive characteristic.

(c) Sand volcanoes. Generally speaking, volcanoes attributable to deaeration are small, a few centimetres in diameter (Burne, 1970), whereas those due to earthquake-triggered liquefaction or to compaction (water expulsion) are larger, reaching metres in diameter (Gill and Kuenen, 1958; Montenat, 1980; Tuthill, 1966; Ambraseys and Sarma, 1969). Volcanoes resulting from compaction cannot be distinguished from those caused by earthquakes on the basis of size.

(d) Clastic dikes. These dikes vary, depending on whether they are filled from above or from below. Dikes filled from above consist of sand, gravel, and even till. The granulometry of the filling material is irregular. These dikes are vertical and are independent of the regional structure. Dikes filled from below are usually the result of liquefaction. They consist of sand, silt or finer material, generally well-sorted. A lateral variation in grain size can be detected, and is probably the result of variations in flow velocity of the material during expulsion. These dikes are also vertical and are often related to the regional structure (for example, parallelism with joints). This is especially true for rocks and in this case indicates emplacement late in diagenisis.

None of the other structural types have special size characteristics that can be used as elements to distinguish them.

Analysis of the information in Table IX demonstrates the influence of a number of factors on the size of structures. These factors are the nature of the cause of the structure, the thickness of the beds affected and the granulometry of the particles.

- Nature of the cause. This factor reflects above all the mechanism involved. Certain causes are local and only affect the surface of a bed. For example, current is generally responsible for small structures involving only a few beds (convolute laminations, load casts). On the other hand, frost results in major structures which are not limited to one type of material or to a well-defined horizon. Similarly, gravity acting on inclined planes can cause large-scale slumping, independently of the lithology.

- Thickness of affected beds. Some mechanisms (density, deaeration) operate only in certain types of materials. The effects are therefore, proportional to the thickness of the beds of these materials. Moreover, this is why laboratory experiments cannot reproduce macroscopic structures. In effect, they are limited, by the space available, to thin beds.

- Granulometry of particles. The size of the structures produced also reflects the nature of the affected soil. For example, liquefaction caused by an earthquake can only affect materials of silt or sand grain size, and convolute laminations caused by currents are mostly produced in sands. These materials cannot generally contribute to formation of large-scale structures.

SYNOPSIS

Two types of structures have been selected as possible sources of criteria for seismic activity: clastic dikes filled from below and sand volcanoes. Although these structures have been chosen, we must not conclude that they inherently provide unique criteria, since, as demonstrated, their origin can vary. Each structure analysed in isolation cannot be taken as a criterion for seismic activity; when associated, however, they can provide a more significant indication.

A - SPECIFIC CRITERIA

The criteria characteristic of each structure selected are those which allow us to distinguish between them and other similar structures that have causes other than earthquakes. Each type of structure will be examined in turn.

1 - Clastic dikes filled from below

The mechanism which forms clastic dikes filled from below involves the injection of liquefied clastic material. According to Leeder (1982), saturated sand will become liquefied if it is subjected to vibrations such as those produced during an earthquake or any other shock. The sand will tend to become more compacted, which will cause an increase in interstitial pressure and result in liquefaction. This process is well known and many authors have discussed it, especially in the geotechnical literature. Leeder (1982) thinks that a

minimum shock of 5.5 to 5.8 on the Richter scale is required to cause liquefaction, and that the process would occur up to a few hundred kilometres from the epicentre. Liquefaction leads to the release of water, which will be expelled if conduits are available. Such pipes frequently appear by breakage of the overlying beds, which sink into the liquefied material. The expelled water carries solid particles having a diameter that is proportionate to the expulsion velocity, although this is generally small, especially in the final phases of the phenomenon. This is reflected by a variation in the granulometry of the expelled material: this variation is observed in the pipe, where the finest material is often in the centre.

The specific criteria for clastic dikes formed in this way are as follows.

(a) Linkage to a source: the clastic dike material is connected to the source from which it came. A parent bed of identical composition is sometimes observed and shows signs of liquefaction.

(b) Internal structure: the dike has an internal structure marked by the preferred orientation of the tabular or elongate grains parallel to the walls of the dike (the result of flow) and by grain size variations from the border to the centre of the dike (because of variations in flow velocity). Nor horizontal stratification should be observed in the filling material.

(c) Nature of dike material: the filling material differs from that of the walls. It is usually a sandy or silty, even-grained material. Coarse elements are rarely observed. Hayashi (1966) established a relationship by which the average diameter of particles in dikes filled from above is larger than that of dikes filled from below. The average diameter in dikes filled from below is the same as that in liquefied sands.

(d) Geometry of dike: the walls of the dike are more or less parallel, are vertical or nearly vertical and have a uniform plane.

These criteria can be used in identifying dikes filled from below by liquefied material. The cause of liquefaction is often, but not always, an earthquake. It may be associated with rapid loading, for example. This type of structure is therefore not an absolute sign of seismic activity. At the very most, we may say that the presence of such structures indicates a high probability (80% ?) of seismic activity.

2 - Sand volcanoes

This type of structure is the second to be selected for establishing criteria of seismic activity, since it is frequently caused by such activity.

As for sand dikes, the formation of sand volcanoes involves the liquefaction of a bed beneath the surface and the expulsion of liquefied material. These structures form cones of material ejected at the surface. The conical form and (sometimes sudden) ejection of material resembles the forms and activity of volcanoes, although on a reduced scale. The name "volcano" comes from such similarities.

We have seen that these structures can have other causes. The specific criteria used in distinguishing those related to seismic activity are as follows:

(a) Linkage to a source: the material of the volcano and that in the pipe are physically linked to the source from which they come. This source, a layer at a lower level, is not always visible. Where it is, signs of liquefaction are observed in it.

(b) Internal structure: the material of the volcano has an internal structure characterized by the parallelism of the beds deposited externally and the orientation of the particles in the pipe parallel to its walls.

(c) Nature of material: as for clastic dikes, to which they are related, moreover, volcanoes consist of sand or silt - materials with high liquefaction potention. Grain size resembles that of clastic dikes.

(d) State of preservation of volcano: sand volcanoes associated with earthquakes retain their form, while those formed by escaping gas tend to collapse or subside.

These specific criteria all define sand volcanoes whose origin is related to earthquakes. Again, these criteria are not absolute and we cannot be completely certain that they indicate seismic activity. An opinion must be expressed in terms of probability. Volcanoes which satisfy the criteria stated have a high probability of formation by earthquakes, even more than for clastic dikes.

Taken together, observations of both types of structure increase the probability of earthquake origin.

B - GENERAL CRITERIA

The general criteria desired are those which will allow positive identification of one or more structures and one or more elements of the geological context, for the purpose of establishing the occurrence of seismic activity. Few writers have touched on this subject. Table X provides a list of criteria evaluated by various authors, who have generally distinguished criteria for the identification of a group of structures. Dott (1963), for example, gives criteria for recognizing structures associated with turbidity currents. Fairbridge (1947) provides criteria for defining slump structures and structures deformed by ice (this category is too broad to be useful for our purposes). Johnsson (1962) gives criteria for ice wedges. Macar (1958) lists criteria for distinguishing the origins of various forms of intraformational folds. Rettger (1935) provides criteria for differentiating between deformations in recent sediments and those in rocks. Hobbs (1976) deals with the same topic. Halicki (1960), without giving actual criteria, discusses the confusion that exists between periglacial structures and those of other origins.

TABLE X

DEFORMATION CRITERIA ACCORDING TO VARIOUS AUTHORS

Structures associated with turbidity currents	Dott, 1963
Slump structures	Fairbridge, 1947
Structures deformed by ice	Fairbridge, 1947
Ice wedges	Johnsson, 1962
Origin of intraformational folds	Macar, 1958
Distinction between deformations in recent sediments and those in rocks	Rettger, 1935 Hobbs, 1976
Deformations caused by seismic activity	Wang et al, 1983a Coates, 1975 Sims, 1975

Only three authors have tried to determine general criteria of seismic activity, with varying success.

1 - Wang et al (1983a) relate seismic activity to liquefaction of silty beds, using examples from the 1976 earthquake at Tangshan, China. They write that identification of old liquefaction phenomena depends on identification of sand volcanoes ("sandboils"). To help in establishing this criterion, they provide a classification of macroscopic characteristics of liquefaction based mainly on the use of aerial photographs. According to the examples they provide, liquefaction structures show up well on aerial photographs, where specific geometric arrangements, such as those given in Table XI, can be distinguished. These writers had the advantage of available photographic documentation prepared soon after the earthquake. Table XII illustrates the practical application of this article.

The application of this method to the study of older structures would be more difficult and there would be no guarantee of success. It might possibly be of use, however, since Chagnon (1968) observed geological structures of unexplained origin in the Baie St-Paul region. He wrote (1969, p8) that [ORIGINAL ENGLISH] "Numerous rounded knobs of low elevation are distributed over the clay basement and consist of sand." These knobs of sand, also observed in the La Malbaie region, are visible on aerial photographs and are similar in some respects to the structures classified by Wang. This approach is interesting, although its application to historical cases remains to be confirmed.

2 - Coates (1975) studied deformations in the recent sediments of the St. Lawrence Lowlands for the purpose of establishing criteria of seismic

activity. He concluded that criteria of sediment deformation by seismic activity can be established, although they only have suggestive value. These are as follows:

- structures in the form of diapirs, especially where truncated;
- horizontal continuity of deformed units;
- presence of thixotrophic phenomena;
- distortions with a vertical trend;
- absence of glacial processes;
- nature of unconsolidated deposits.

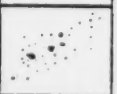
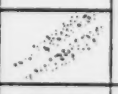
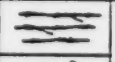
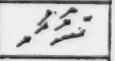
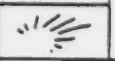
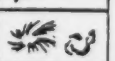
CATEGORY OF PATTERN	SUBDIVIDED PATTERN	LEGEND	GEOMORPHIC AND TOPOGRAPHIC FEATURES	PRINCIPAL MODE OF SURFACE WAVE	FIGURE NO.
SCATTERED STARS (s.s.)	SPARSELY s.s.		ON PLAINS AWAY FROM RIVER BANK, SIMPLE GEOMETRY	EVENLY TRANSMITTED SURFACE TRAVELLING WAVES	1a
	DENSELY s.s.				1b
	CLOUDILY s.s.				1c
NETWORK	BRANCHES		ON THE CONVEX SIDE OF RIVER BENDS, TOPOGRAPHICALLY LOW, NEAR THE RIVER	STATIONARY SURFACE WAVES REFLECTED AND FOCUSED WITHIN RIVER BEND	2a
	ARTERIES				2b
	RADIATION				2c
TORTILE	BROOM		INSIDE RIVER BENDS, TOPOGRAPHICALLY LOW PLAINS	RESULTANT WAVE FRONT VECTORS FROM MULTI-DIRECTIONAL REFLECTION, INTERSECT TO FORM TORSIONAL MOVEMENT OF GROUND	3a
	VORTEX				3b
	CURLY HAIR				3c

Table XI - Macroscopic criteria of liquefaction (Wang et al, 1983a)

Table XII - Practical application of liquefaction forms (Wang et al, 1983a)

Category of pattern	Subdivided pattern	Spacing of sandboils (m)	Index of damage (approx.)	Status of damage
Scattered stars (s.s.)	Sparsely s.s.	≈100	0.20	Slight damage: on level ground uneven settlement of foundations causes cracks in walls. Because shear wave cannot be transmitted through liquified layers, liquefied area often does less harm to facilities on ground.
	Densely s.s.	<50	0.4	
	Cloudily s.s.	<20	0.4	
Network	Branches	30 ~ 50 (in row)	0.9	Intermittently distributed damage, i.e., buildings or facilities collapse or stand within half-spacing of arteries. Heavily destroyed areas are concentrated at the center of the river bend. Horizontal swaying may be the main mode of ground movement.
	Arteries	≈20 (minimum)	0.6	
	Radiation	—	0.9	
Tortile	Broom	<1000 (radius of curvature)	0.8	Heavily damaged under extensive horizontal torsional shearing. Buildings collapsed, ground unevenly settled, soil strata distorted, tension–torsional surface ruptures widespread over the site.
	Vortex	500–1000 (outer diam.)	0.9	
	Curly hair	≈30 (width of curl)	0.7	

NOTE: Index of damage of a natural village means the weighted mean of the number of damaged houses of a certain equivalent style, e.g., brick houses. Thus

$i_b = \sum_k i_{bk} n_k / N_b$ where b represents a kind of brick house; n_k is the number of brick houses; and $N_b = \sum_k n_k$ is the total number of brick houses in the natural village.

These criteria are very general and are not supported by specific explanations in the text. They warrant review and discussion, one at a time.

- Structures in the form of a diapir, especially when truncated: the origin of this criterion is not obvious from a reading of the text. The author indicates that, in his opinion, a structure in the form of a diapir is a structure which displaces and sometimes cuts an overlying formation. He seems to apply this term to both a fold with a flattened top and to a clastic dike. The use of the word "diapir" in this context is quite misleading, since this term is used most often in geology to describe upward movements of salt resulting from contrasts in density. This criterion does not appear to be clear, except when it is applied only to clastic dikes.

- Horizontal continuity of deformed units: this criterion implies that an earthquake affects a particular horizon during or after sedimentation. It is logical to come to this conclusion and this criterion is of value.

- The presence of thixotropic phenomena: the author is probably referring here to signs of reworking or, more specifically, liquefaction. These signs are rare and only sand volcanoes seem to be of use. This criterion is also worthwhile.

- Distortions with a vertical trend: the author seems to be referring in this case to structures like clastic dikes. In the text, he mentions folds of which the axis and limbs are mostly vertical; this does not seem valid as a criterion, since the vertical trend of deformation structures is not an exclusive feature of those resulting from earthquakes.

- The absence of glacial processes: this criterion would be useful in another geological setting, such as California. In the area of interest to us, glacial processes are present everywhere and it is difficult to demonstrate, apart from exceptional cases, that they are not active or have not been so.

- Nature of unconsolidated deposits: this criterion is obscure and seems to depend on other criteria. In fact, certain structures are formed only in well-defined soil types (such as sand volcanoes) and are not observed in other types which have also been affected by seismic activity.

We will return below to all the criteria selected. Let us mention that Coates (1975) concludes his study with the statement that most deformations observed in the St Lawrence Lowlands are of glacial origin.

3 - Sims (1975) has provided a series of criteria for the establishment of a correlation between deformation structures and seismic activity. These are as follows:

- proximity to a seismic zone that is currently active;

- presence of sediments with a high potential for liquefaction, such as saturated sands and silts of low specific gravity;

- similarity with structures formed experimentally;

- small internal structures, within deformed zones, that suggest liquefaction;

- structure limited to a single stratigraphic horizon;

- zones of structures distributed over large areas;

- absence of the influence of slopes, slope breaks or other sedimentologic, biological or deformation processes.

Before we look at these criteria, it will be helpful to point out that Sims' studies concerned an area unaffected by glaciation. The distinction of deformation structure origins is therefore much simpler.

The first criterion concerns the proximity of a source of seismic activity and is quite obvious. The second involves the presence of liquefiable sediments. This indicates that Sims identifies deformation structures resulting from earthquakes with the phenomenon of liquefaction. Moreover, this is the formation process suggested for structures selected in our study (clastic dikes and sand volcanoes).

The third criterion concerns the similarity to structures reproduced experimentally. Sims is undoubtedly referring to the structures reproduced by Kuenen (1953), such as pseudonodules and convolute laminations, structures which Sims observed in the sediments of the Van Norman reservoir after the San Fernando earthquake in 1971. We have not accepted these structures, since they are formed by numerous processes and are confused with glacial effects. The structures chosen (clastic dikes filled from below and sand volcanoes) have not been reproduced in the laboratory but have been observed visually or directly. This third criterion is therefore less useful in the geological setting of the St Lawrence Lowlands.

The presence of internal structures is a fourth criterion which we can use, even though its application is made difficult by the interference of frost action. The fifth criterion concerns the observation of structures in a particular horizon. It is similar to the criterion proposed by Coates (1975) concerning the lateral continuity of deformed units. It should be retained as a criterion .

The lateral extent over large areas (the sixth criterion) is difficult to check. It is valid if we have precise stratigraphic reference points. Moreover, it requires that there be actual lateral continuity. The seventh criterion involves the absence of other formation processes and resembles that of Coates (1975) on the absence of glacial processes. As for Coates' criterion, it is difficult to apply in our local geological setting.

Not all the criteria proposed by Sims (1975) can be applied to the St Lawrence Lowlands, since glacial effects mask the effects of other processes. However, several are relevant and have been selected.

The specific and general criteria described in this report are the only ones found during the bibliographical research. Some have been established positively by observation and by experiments and apply to local conditions. However, we reiterate that no criterion provides absolute assurance that seismic activity has occurred.

CHAPTER V

REVIEW OF THE LITERATURE ON LABORATORY EXPERIMENTS AND DEFORMATIONS

INTRODUCTION

The purpose of this chapter is to review the literature on laboratory experiments intended to reproduce sedimentary structures associated with earthquakes. As indicated earlier, the most common of the deformations associated with earthquakes are (1) slumping, (2) sand volcanoes and (3) sand dikes filled from below.

Most publications concerning the observation of plastic deformation in the laboratory date from the period between 1900 and 1960. Kuenen (1958) performed several laboratory experiments which were not subsequently repeated. In the late 1960s, a number of authors (Anketell and Dzulynski, 1968; McKee and Goldberg, 1969) returned to the task, repeating certain experiments to simulate pillow structures in particular. These experiments remained descriptive. Ambraseys and Sarma (1969) were the first to attempt the measurement of earthquake effects on sediments, notably by quantifying observations leading to a definition of the role played by parameters such as critical acceleration of particles and specific gravity of soils involved. However, their approach was concentrated mainly on liquefaction studies of sands, although this could be related to structures such as sand dikes.

Only in the early 1970s, however, with the article by Allen and Banks (1972), did a quantitative approach appear for the formation of convolute laminations in newly-formed deposits. This paper is especially interesting because it is directly concerned with making models of sedimentary structures. Parallel to this work, increased efforts to study the dynamic properties of soils generated numerous publications, largely beyond the general framework of this project; they should nevertheless be consulted if laboratory work results from our study.

Publications evaluated to date indicate that sedimentary structures (such as sand dikes) produced during telluric vibrations are closely related to the nature of the soil, its manner of deposition, its maturity (or degree of consolidation) and, finally, the conditions of interstitial water pressure. Naturally, the main element (or necessary condition) is the intensity of earthquakes and their duration.

The literature covered in this report can be divided into two groups: (1) articles dealing with the theoretical aspects (or model-making) of causes and of the dynamic behaviour of soils, and (2) those concerning sedimentary structures reproduced in the laboratory. The aspects covered in the first group are mostly related to the sedimentation process and liquefaction. The analysis and synthesis of the literature will therefore be presented in two stages, corresponding to the two groups mentioned.

ANALYTICAL STUDIES OF DEFORMATIONS

As indicated at the beginning of this section, the late 1970s seem to be a turning point in the simulation of deformations associated with materials high

in water content. While the article by Kuenen (1958) tried to indicate the important role of simulation experiments in the laboratory on reduced models, the article by Anketell and Dzulynski (1970) clearly indicated that an attempt must be made to quantify the processes, thus foreshadowing the increased use of computer modelling. In their papers, Anketell and Dzulynski (1970) and Selley (1969) stress the importance of the transition of a soil mass through a state approaching a liquid. A review of the literature on this subject showed use that soil can achieve such a state through two distinct processes: fluidization and liquefaction. Fluidization results from the effect of density gradients and differential consolidation in a sediment, leading to a migration of water to other areas of the soil and thereby creating an overpressure of water in these locations. This overpressure of interstitial water causes a reduction in effective stresses, which then tend toward zero. Liquefaction, on the other hand, is the transformation of a soil into a liquid as a result of vibrations that cause an increase in interstitial pressure, hence a reduction in effective stresses, such that:

$$\sigma' = \sigma - \mu$$

where ? is the total stress, σ' is the effective stress and μ is the pressure of interstitial water.

Publications consulted on this topic fall into two categories: (1) liquefaction and (2) sedimentation - fluidization. Those studying sedimentology often refer to concentration and density gradients that occur during sedimentation of recent deposits. The studies on liquefaction also deal with non-indurated, often loose sediments. On the basis of a few authors who deal with the subject, therefore, we will consider a number of analytical aspects of these two phenomena, which are very important (Sims, 1978) in the formation of sand dikes and mud volcanoes, among other things.

Liquefaction

The phenomena of liquefaction has raised much interest in the past few years. As early as 1936, Casagrande provided some explanations on the process of liquefaction, as previously mentioned. More recently, the article by Seed (1968) provided a better understanding of the dynamic behaviour of sand under cyclical loading, such as that caused by earthquakes. A review of all the literature on this subject would be very tedious and would exceed the scope of this project. However, it is of interest to summarize a number of principles to see if we can discover some conditions favourable to liquefaction and the kinds of deformations associated with it. We have already indicated that sand dikes filled from below result in most cases from liquefaction caused by earthquakes. Unlike fluidization, liquefaction is caused by vibrations transmitted to soil and, especially, to the water. The conditions favouring liquefaction are found when the sand is loose and saturated with water. Under such conditions, an earthquake can cause enough vibration to liquefy the soil. Seed and Idriss (1971, in Ishirhara, 1978) suggest a procedure for evaluating the liquefaction potential of a soil:

(1) evaluation of the history of dynamic stresses of the site;

(2) determination of the shear stresses required for liquefaction of the deposit at various depths;

(3) determination of the susceptibility of the sand to liquefaction at various depths by comparison with the shear stresses that can be generated by an earthquake of given intensity.

Several publications, including those of Siro (1976) and Seed (1968), indicate that soils which have already been liquefied become more compact and therefore less susceptible to subsequent liquefaction. The propensity of a heavily overconsolidated sand to liquefaction is much less than for a loose sand; furthermore, it would require an earthquake of longer duration or of greater intensity to liquefy a consolidated sand than for a loose sand. Holtz and Kovacs (1981) prefer to use the term "cyclic mobility", rather than "liquefaction", in such cases to correctly reflect the influence of the degree of consolidation on the number of cycles required to liquefy the soil.

The paper by Ishihara (1978) is very interesting regarding conditions favouring liquefaction. Ishihara (1978) remarks that, according to analysis of several laboratory experiments, it seems that liquefaction almost always occurs at the moment when maximum stress is reached during irregular loading (Figure 14). After this state, the interstitial pressure remains almost constant as long as the conditions of non-drainage are maintained. He also notes that liquefaction occurs around 5 to 30 seconds after the start of "major shaking" for most earthquakes. Maintenance of zero effective stress in the sediment depends on the drainage system and maintenance of vibrations. Ishihara (1978) describes the various types of waves produced during an earthquake and suggests that, according to his experiment, two types may be considered: (1) a shock wave and (2) a vibration wave. The first corresponds to a wave with one or two peaks of amplitude 60% greater than the preceding peaks. The second corresponds to a wave of which more than three peaks, on the same side of the maximum stress, have an amplitude greater than 60% of the maximum occurring in the trace (Figure 15). He also observes that a wave of the vibration type is more likely to produce soil liquefaction.

The ideal conditions for liquefaction of a sand are thus as follows:

(1) high porosity;

(2) complete saturation;

(3) limited drainage;

(4) occurrence at shallow depth (less than 20 meters);

(5) wave of the vibration type of long duration, or of the shock type of high intensity.

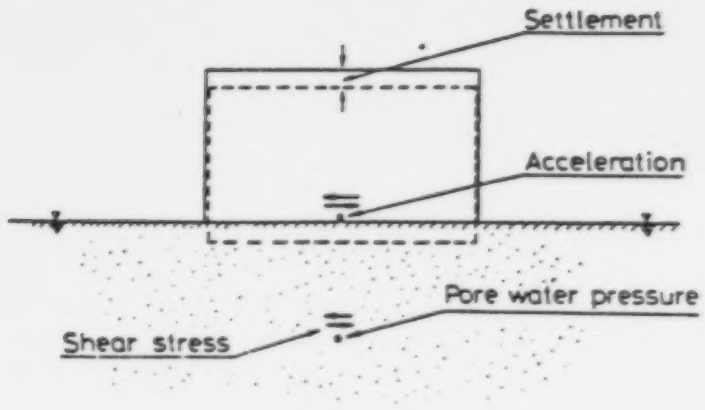


Fig. 1 Phenomena associated with liquefaction of loose sand deposit

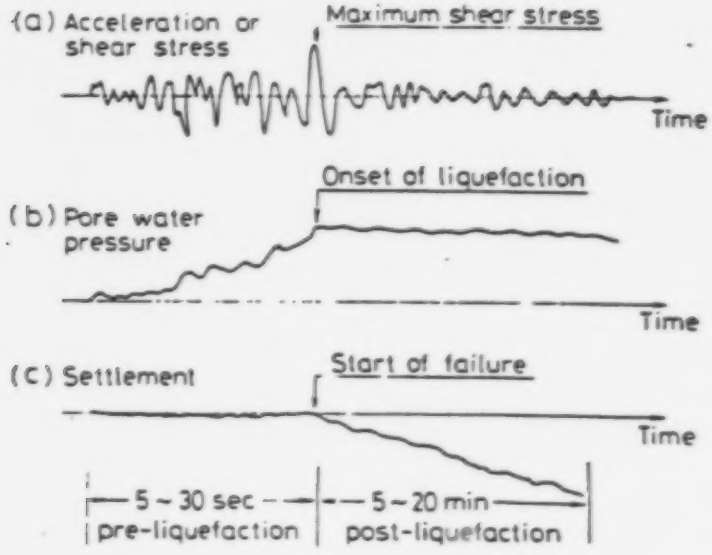


Figure 14 - Sequence of events associated with liquefaction at various moments (Ishihara, 1977).

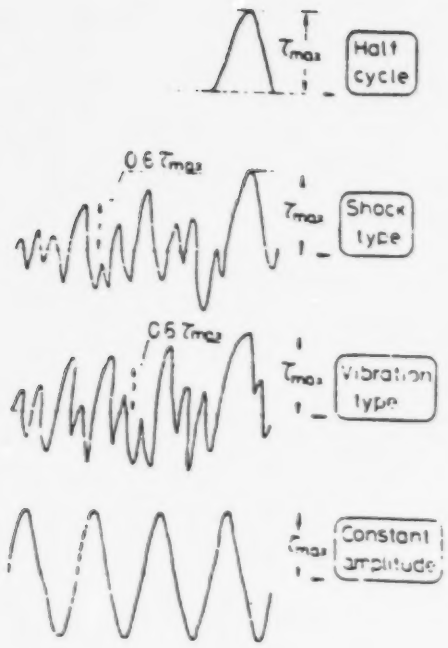


Figure 15 - Classification of wave forms associated with irregular loading (Ishihara, 1977)

Such conditions should be evaluated during the performance of laboratory experiments. As we will see below, most experiments for the purpose of laboratory reproduction of deformations associated with seismic activity were done under conditions which did not readily allow correlation with conditions in the field. The experiments on fluidization seem to correspond more to field conditions, although only for certain aspects.

Sedimentation - fluidization

The sedimentation of particles in an aquatic environment has been the subject of numerous articles over several decades. However, as indicated by Butrym et al (1964), the problems related to reverse concentration gradients in a sediment are still difficult to approach. Concerning the basic elements of theories of sedimentation, the publications by Middleton and Hampton (1973) and Potter et al (1980) are of special interest. Those authors describe the classic theories of sedimentation: in other words, those relying principally on Stokes' Law. On the other hand, in sediments such as turbidites, the sediment concentration is such that Stockes' Law no longer applies. What then occurs in the sediment column, at rather high concentrations, is sedimentation known as "hindered settling", as illustrated in the articles by Kynch (1952) and Migniot (1968), as well as McRoberts and Nixon (1976). The main purpose of this review of sedimentation is to emphasize that stratification of density or concentration in a sediment occurs early in sediment formation. Situations such as those found near glaciers or fluvioglacial deltas favour a sedimentary basin evolution which tends to produce stratification, whereby sands and gravels may be deposited over soft clays, thus producing a density gradient and sometimes a concentration gradient (Allen, 1977). In 1970, Allen provided an analytical model of a situation favouring pillow structures (Figure 16). In this example, he mentions that:

> [ORIGINAL ENGLISH] These structures represent a case of gravitational instability in which the different parts of the system in a liquefied state have moved relatively prior to lithification in response to buoyancy forces. (Allen, 1970, p 86)

Figure 16 - Load casts formed at the interface between sand and clay beds (Allen, 1970)

Allen (1970) states that the density of fresh mud is 1.5 g/cm^3, while that of overlying loose sand is 2.0 g/cm^3. This arrangement is therefore metastable and any vibration will disturb it, somewhat as Kuenen said in 1958. The pillow forms illustrated in Figure 16 thus result from dynamic deformation during sinking of the soil mass of greater density. For a better understanding of this description of Allen (1977), we will repeat below some

of his explanations of the transformation of turbidites into sediments with a reverse density gradient. This situation can occur, especially in a heterogeneous sediment consisting of fine and coarse particles. The density (γ) of a dispersion of grains is related to the concentration of particles (C_1) by the following equation:

$$\gamma = \rho + C_1 (\sigma - \rho)$$

where ρ is the density of water and σ the particle density.

The overall density of the dispersion thus increases linearly with concentration. When a graded turbidite becomes liquefied, the coarser grains at the base of the column sink more rapidly than the finer grains at the top of the soil column (Figure 17). This differential velocity is confirmed by Stokes' Law, which states that the settling velocity of particles is proportional to the square of the diameter. Bagnold (1954) says that the distance between the particles varies inversely as their fractional concentration, so the concentration in the lower part can diminish more rapidly with time than in the upper part. In a turbidite, therefore, there is grading toward the top in which the relative distance between particles, for comparable concentrations, increases upward. Thus, the dispersion of a soil column of a turbidite which has been fluidized will be such that the coarser grains at the base will fall more rapidly, leaving a zone within the column that will decrease in density. Since the particles in the upper part fall more slowly, the concentration in this zone could decrease more slowly, Hence the zone of more rapid reduction in concentration could reach a concentration level that is even lower than that of the zone above, creating a reverse density gradient. Therefore, the concentration gradient after sedimentation could decline or even become negative. Allen (1977) proposes the following relationship:

$$dc/dt = -C (dw/dy)$$

This shows that the rate of change in particle concentration for a given grain [size] increases with local concentration and with the velocity gradient of the falling particle. Thus, where the gradient is positive at first, it is possible with sedimentation that the concentration at a given level will decline with time. There is therefore a zone in the sediment column which could become deformed because of the concentration gradient and its fluidized state.

Allen (1977) states that this process requires a number of factors:

(1) the potential existence in the sediment of a gradient in settling velocity;

(2) generation of interstitial pressure caused by various factors, such as those mentioned earlier, including earthquakes;

(3) a sufficient period of fluidization of the bed for completion of resedimentation.

According to this author, such conditions would favour the formation of convolute laminations. Thus the phenomena associated with sedimentation and fluidization can lead to flexible deformation structures, such as convolute laminations, which could result from earthquakes.

Allen and Banks (1972), by digital analysis, obtained deformations in cross-bedded deposits by simulating the combined action of soil liquefaction and the dragging effect of a current at the surface of the soil (Figure 18). They conclude, among other things, as follows:

> [ORIGINAL ENGLISH] In the light of our model, we suggest that the occurrence in space and time of deformed cross-bedding in waterlaid sediments may be a useful guide to tectonic activity involving earthquakes. (p 280)

However, they did not succeed in reproducing in the laboratory the conditions which they simulated by computer. The purpose of the following section, in fact, is to review the laboratory data which exists on intraformational deformations that may be associated with seismic activity.

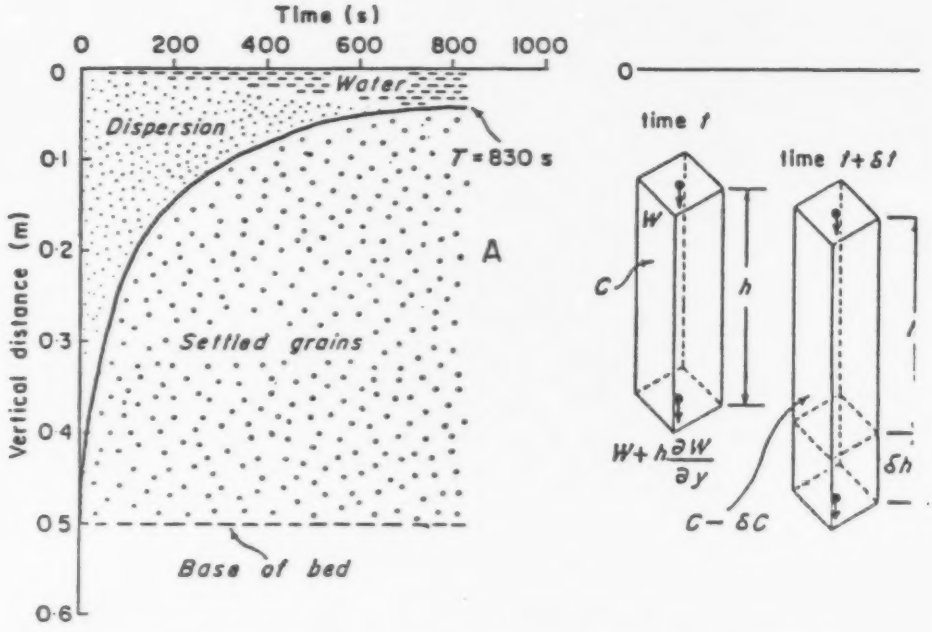


Figure 17 - Behaviour of a dispersion of grains during accumulation of particles; example of resedimentation of a turbidite 0.5m thick following liquefaction (Allen, 1977)

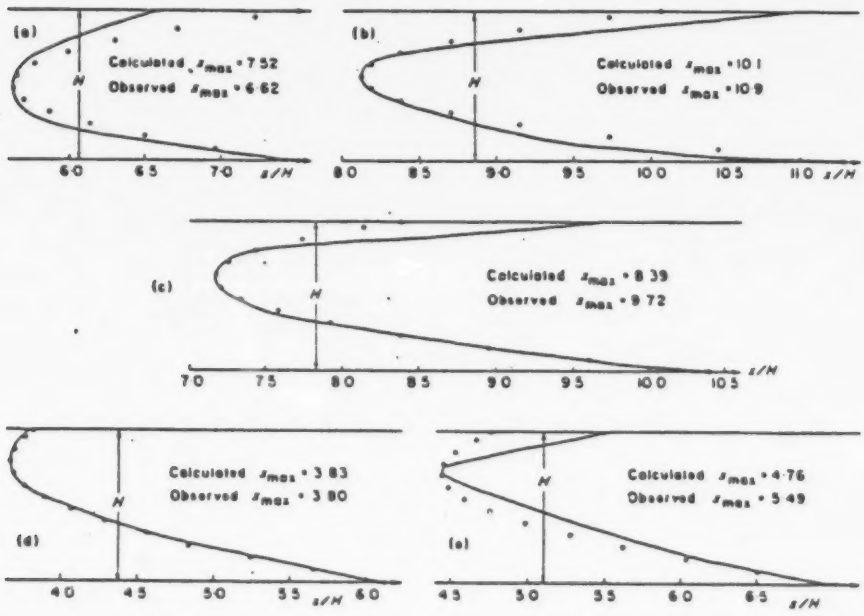


Figure 18 - Calculated deformations (dots) and observations of deformed beds in five different cases (Allen and Banks, 1972)

SEDIMENTARY STRUCTURES WITH PLASTIC DEFORMATIONS

REPRODUCED IN THE LABORATORY

Articles found in the literature on this subject are discussed below. The main articles are described and analysed in chronologic order, so that we may better follow the evolution of methods used. Before we go further, we should point out that the only documents selected were those which concerned plastic deformation or secondary sedimentary structures found in soft sediments during deformation. We were thus able to eliminate all articles dealing with the laboratory reproduction of other sedimentary structures (such as ripple marks and other current structures). Table XIII summarizes a number of characteristics of experiments done in the laboratory to produce convolute laminations and other types of flexible deformations.

As indicated earlier, the article by Kuenen (1958) strongly influenced sedimentologists and, in a way, marked the end of the so-called observation experiments (those which only describe deformations). For this reason, the documents are divided into three groups: (1) those before 1958, (2) those between 1958 and 1970 and (3) those after 1970. The second boundary is characterized principally by the appearance of articles that are increasingly quantitative in nature, aimed at preparing models.

TABLE XIII - Information on a number of laboratory experiments producing structures such as convolute laminations or other flexible deformations.

AUTHOR (S)	MATERIAL	STRUCTURE	THICKNESS OF BEDS (cm)	AMPLITUDE (cm)
Deely, 1916	sandy wax on "pitch"	convolute laminations	1-3	2
Kindle, 1917	sand on clay with thin beds of plaster	inclined folds	2-3	10
Rettger, 1935	beds of sand and clay	slumping, folds, fault	1-3	1-3
Kuenen, 1958	sand on mud	sausage-shaped convolute laminations	2 for the sand	5
KcKee et al, 1962a, 1962b	sand	convolute laminations	2-5	2-20
Dzulynski and Walton, 1962 [?]	sand on clay	convolute laminations, flame structures	2-5	5-20
Butrym et al, 1964	sand on clay	load cast, diapir, convolute laminations	0.1-1	0.5-1
Selley, 1969	sand on kaolin	convolute laminations	0.1-1.5	0.2-4
Weaver and Jeffcoat, 1978	calcareous sand and calcareous mud	pillow	0.5 for the sand	

Period Prior to 1958

The first laboratory experiment for the purpose of reproducing convolute laminations was conducted by Deely in 1916. He tried to illustrate the effect of a density gradient by using materials such as sand and wax. In Deely's opinion (1916), such deformations resulted from climatic variations, especially frost action. According to him, such deformations had already been described by Fisher in 1866.

At about the same time, Kindle (1917) made laboratory reproductings of intraformational deformations similar to those he had observed in Nova Scotia and southern Ontario. According to him, such observations had been made previously by Emmons (1847). The main purpose of Kindle's experiments (1917) was to reproduce load casts. In them, he used clayey sediments at the base (about 4 cm) covered with a fine layer of coal mixed with plaster of Paris (since this material was stiffer). Over these sediments, he simulated the formation of sandy delta and observed the resulting deformations in them (such as inclined folds). This experiment varied the distribution of sediment load, the main cause of deformations in Kindle's opinion (1917). Such variations in sediment load could be related to uneven erosion and sedimentation rates at different points in the basin. Kindle (1917) also saw iceberg action as a possible agent of sediment overload.

Schofield and Keen (1929) reported what seems to be the first laboratory observation of mud volcanoes. In this case, however, the cause appears to be related to the phenomenon of syneresis, which causes the formation of cracks along which surplus water flows. This water migrates upward, carrying with it particles which form a small cone when they reach the surface. This phenomenon seems to occur when the suspension reaches a critical concentration.

Rettger (1935) published interesting laboratory results involving the reproduction of several structures, including convolute laminations and sand volcanoes. This document provides the first experimental basis for the study of intraformational deformations. Rettger (1935) attempted to produce deformations associated with the following phenomena: (1) falling mass, (2) slumping, (3) load casts, (4) differential movement, (5) differential loading, (6) sand volcanoes ("landscape marble") and, finally, (7) deformations in sediments above an active fault. These experiments were done in a metal tank 1.5 m long, 30 cm high and 15 cm wide. Another similar tank was also used, but it included a segmented base to reproduce the effect of a fault. Observation of deformations in the soils was possible by means of artificially coloured sand horizons and by the occasional deposition of the sediments in suspension. Although Rettger's paper (1935) mentions several possible causes, he says nothing about earthquakes. His article was referred to later by McKee et al (1953), who discussed similar structures.

In 1956, Stewart suggested the role of gases as another deformation process. Using laboratory experiments on sands, he showed that gas bubbles rising in a sediment cause typical deformations. Stewart's equipment consisted of a cylinder 33 cm high and 10 cm in diameter. The cylinder allowed water in at both ends. Stewart (1956) hoped to simulate a strand zone. Thus the ebbing tide was simulated by desaturation, or even drying of the sand. The rising tide was represented by the entry of water from above, suggesting the arrival of waves, while the entry of water from below corresponded to the rise in the water table. In this way, he trapped air bubbles in the upper part of the sediment; these, pushed by the water coming from below, were forced to the top, causing deformations in the upper part of the soil. In a case such as this, deformations occur in a soft (loose) soil in shallow water. At greater depths, the air could be dissolved in the water.

This paper marked the end of the pre-1958 period. Up to this point, the article by Rettger (1935) was the most striking prior to that of Kuenen (1958).

Period from 1958 to 1970

For this period, we have chosen to start with the article by Kuenen (1958) entitled "Experiments in Geology". Before we describe Kuenen's results, we should mention that he was trying to demonstrate to his colleagues the advantages of laboratory experiments in simulating geological processes. In the early 1970s, computer simulation became the fashion. This period, therefore, has perhaps provided less laboratory experimentation, although it began with work (Kuenen's) which considered vibrations associated with earthquakes. However, experiments appeared to improve in control as developments progressed in soil mechanics, especially the dynamic behaviour of soils and the liquefaction of sands.

The paper by Kuenen in 1958 was thus intended as an illustration of the importance of laboratory experimentation that simulated certain geological processes (such as erosion, tectonics and deformations). The article is significant, in that it clearly adds to [the understanding] of causes already known to result in intraformational deformations:

> The idea I wanted to test was whether earthquake vibration could break down the strength of a thixotropic mud and induce a cover of sand to start load casting because of its higher density. (Kuenen, 1958, p. 18).

This experiment is thus the first one to be formally performed for the purpose of evaluating the effects of vibrations on sediments as a deformation factor. In our study, therefore, this article marks an important stage because of this aspect, and not because of the overall treatment of the problem. In his experiments, Kuenen (1958) used a hammer attached to the eccentric shaft of a motor to simulate the effects of an earthquake. However, no measurement of acceleration values is provided in this article. Figure 19 illustrates the results he obtained. In the same article, Kuenen also attempted an explanation of mud volcanoes which had already been observed by Rettger (1935).

McKee et al (1962a and 1962b) successfully reproduced in the laboratory new conditions favourable for the production of intraformational deformations. They also created convolute laminations using drag forces above the sediments, as can occur on strands, especially those with strong tides. The experiments were done in a large basin 4.5 m long, 0.8 m wide and 0.6 m deep. They used "Ottawa sand" and grains of magnetite to indicate bedding.

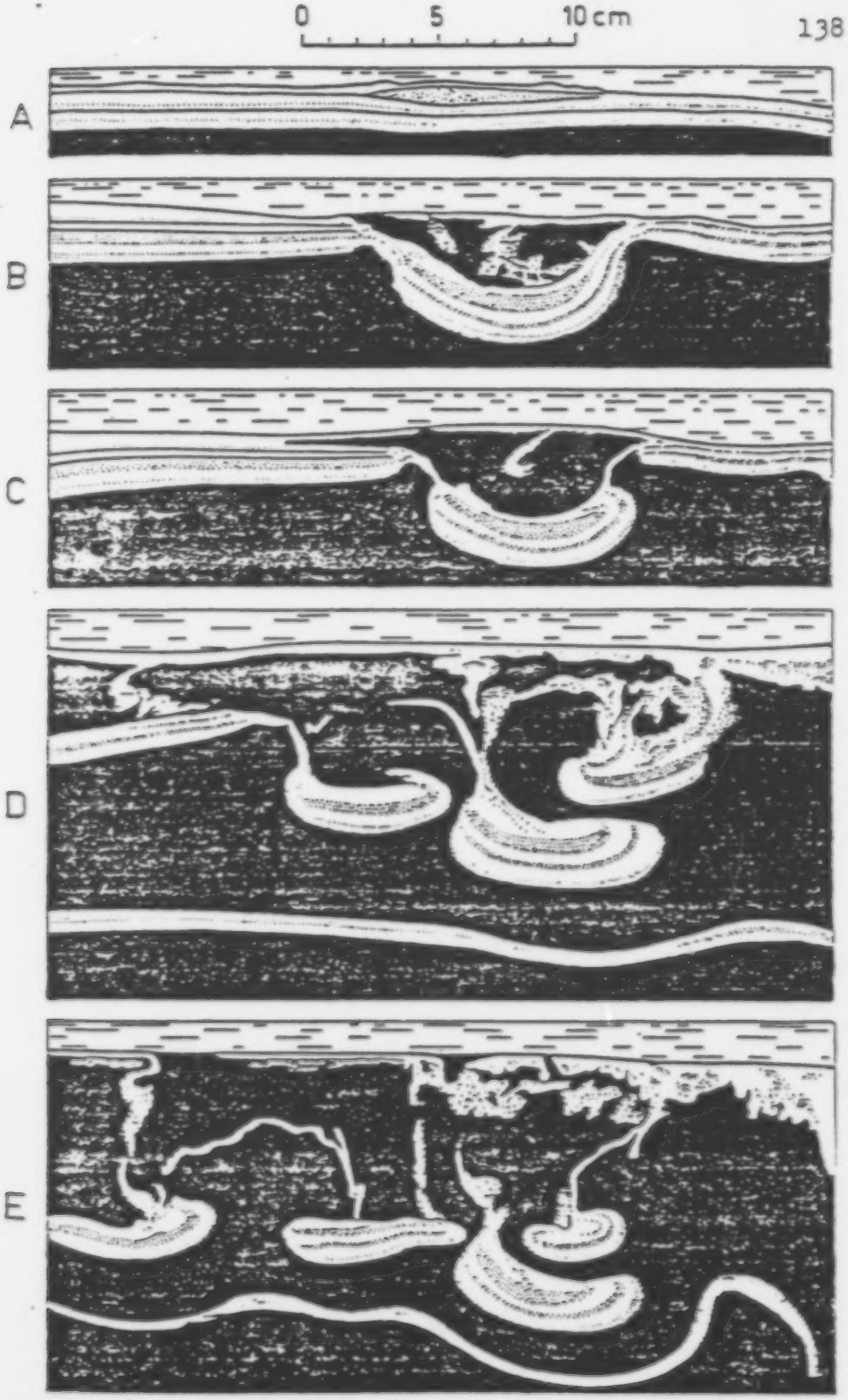


Figure 19 - Formation of pseudonodules in five stages. A bed of sand sinks into the mud as a result of earthquake simulation. (Kuenen, 1958)

Dzulynski and Walton (1963) also conducted experiments to simulate load casts. For this, two sets of experiments were done: (1) with a base bed of soft clay (1 to 3 hours of consolidation) and [(2)] with a bed of stiffer clay (more than 10 hours). The authors used these experiments to attempt to demonstrate that uneven sedimentation favours this type of structure (see Figure 20) more than do irregularities in the initial surface of the clayey bed.

They agree with Kuenen's idea regarding the role of seismic vibration in forming such structures.

Butrym et al (1964), from laboratory experiments, re-interpreted deformation structures once linked to the effects of ice alone. The "involutions" which they observed were said to be caused by load phenomena ("load deformation").

Dzulynski (1965) used laboratory experiments to illustrate the role of currents in surface deformations (Figure 21). Later, Dzulynski and Radomski (1966) went further in this study with their publication on the drag effects of turbidity currents. Under certain conditions, such currents could drag the upper layers of the underlying soil. This situation is clearly indicated in Figure 21, the result of laboratory experiments.

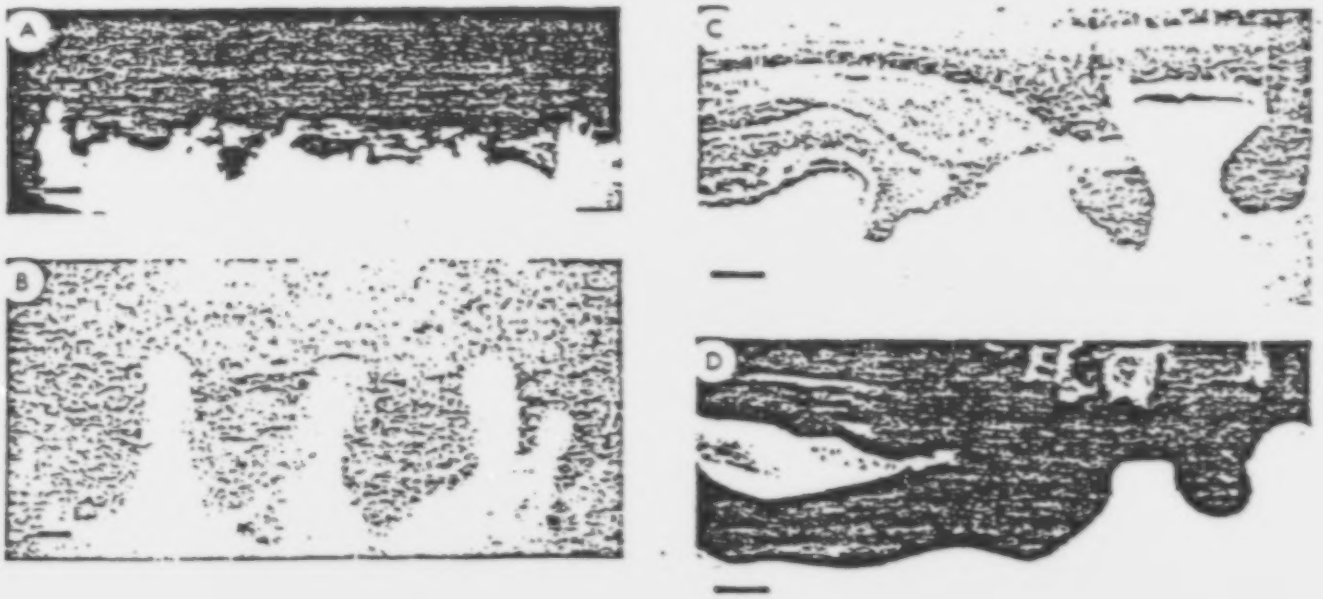


Figure 20 - A - Irregular contact between sand and mud
B - Flame structures caused by vibrations
C - Asymmetric flame structures
D - Load cast
(Dzulynski and Walton, 1963)

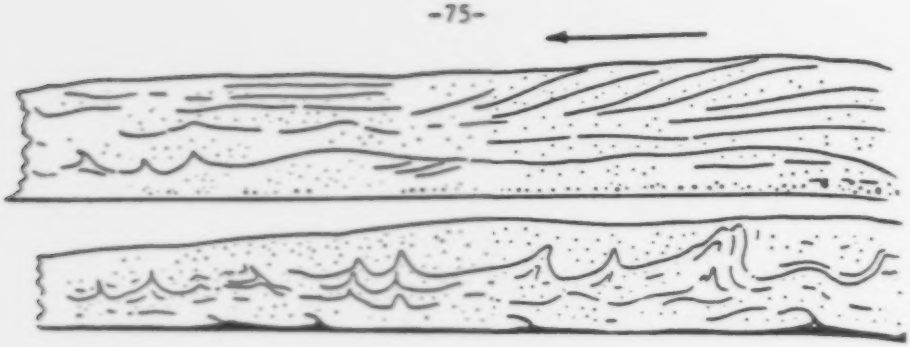


Figure 21 - Internal structures in an artificial turbidite (Dzulynski, 1965a)

In 1968, Anketell and Dzulynski began laboratory experiments which took into account density gradients, thus initiating the first systematic work on the characterization of soils that are used and of their physical state. In particular, they studied turbidites, also considering vibrations as the trigger for deformations.

The article by McKee and Goldberg (1969) is one of the last in which laboratory experiments are used to illustrate deformation types. It is a complete synopsis of the ways in which convolute laminations are obtained. Table XIV summarizes the various experiments and the conditions required to produce a given structure. This article refines the definition of various deformation types to a degree never before seen. However, despite the rather recent date of this publication, it does not consider vibrations associated with earthquakes. The article by McKee and Goldberg (1969) is important, in a way somewhat similar to the one by Kuenen, but it also marks the end of a period in which laboratory experiments were mostly descriptive. Starting in the late 1960s, a better understanding of soil mechanics brought a major change in the approach to laboratory experiments, which became increasingly complex.

TABLE I. VARIATION IN FACTORS AND THE RESULTING STRUCTURES IN EXPERIMENTS 1-15

Experiment number	1°	2°	3	4	5°	6°	7	8	9	10	11°	12°	13	14	15
Resulting structure	Convo-lute	Convo-lute	None	None	Convo-lute	None	Irregu-larly Con-torted	Convo-lute	Weak Con-volute	Convo-lute	Thrust Con-torted	No con-volute; way from deposi-tion	Over-turn and Thrust	None	None
Concentration of load: Blanket (B) or differential (D)	D	D	B	B	D	B	B	D	D	D	D	B	D	B	D
Base sediment: sand (S) or mud (M)	M	M	S	S	M	M	S	S	S	S	S	S	S	S	S
Salt water: present (P) or absent (A)	P	P	P	A	A	A	A	A	A	A	A	A	A	A	A
Mud deposition: Lateral by even current (C), crystal movement (R), or vertical by gravity (G)	C	C	G	G	C	C	G	C	C	C	G	G	G	R	R
Organic matter: with (W) or without (O)	W	W	O	O	O	O	O	O	O	O	O	O	O	O	O
Surface of base: crystal (R), flat (F), or slipping (D)	D	F	F	F	F	F	R	F	D	F	R	R	D	F	F
Type of loading: Lateral (L) or from above (A)	A	A	A	A	A	A	L	A	A	A	L	L	L	L	L
Water during loading: crystal (R), quiet (Q), or even flow (E)	Q	Q	Q	Q	Q	Q	R	L	E	Q	Q	Q	Q	R	R

TABLE XIV - Variation in factors and the resulting structures of flexible deformations produced in the laboratory (McKee and Goldberg, 1969)

This period ends with the article by Selley (1969), who tried to reproduce in the laboratory conditions comparable to those he called "fossilized quicksands". With its references to the book by Terzaghi and Peck (1967), this article shows a new interest in soil mechanics on the part of sedimentologists. Selley's experiments thus attempted the reproduction of quicksands. Selley (1969) realized the importance of soil strength parameters and the role of interstitial pressure in the effective stresses in a soil. He also distinguished between two classes of quicksands: (1) those which have a sufficient clay fraction to cause them to behave in a way which he qualifies as thixotropic, and (2) well-sorted sands in which intergranular friction is reduced by high interstitial water pressure. The experiments by Selley (1969) resulted in the formation of convolute laminations after liquefaction of the sand brought on by vibrations (Figure 22). He obtained the same results by agitating the water at the top of the tank, which had the effect of increasing interstitial water pressure and liquefying the sand. In the generation of quicksand conditions, in his opinion, the action of currents cannot be felt several metres below the surface.

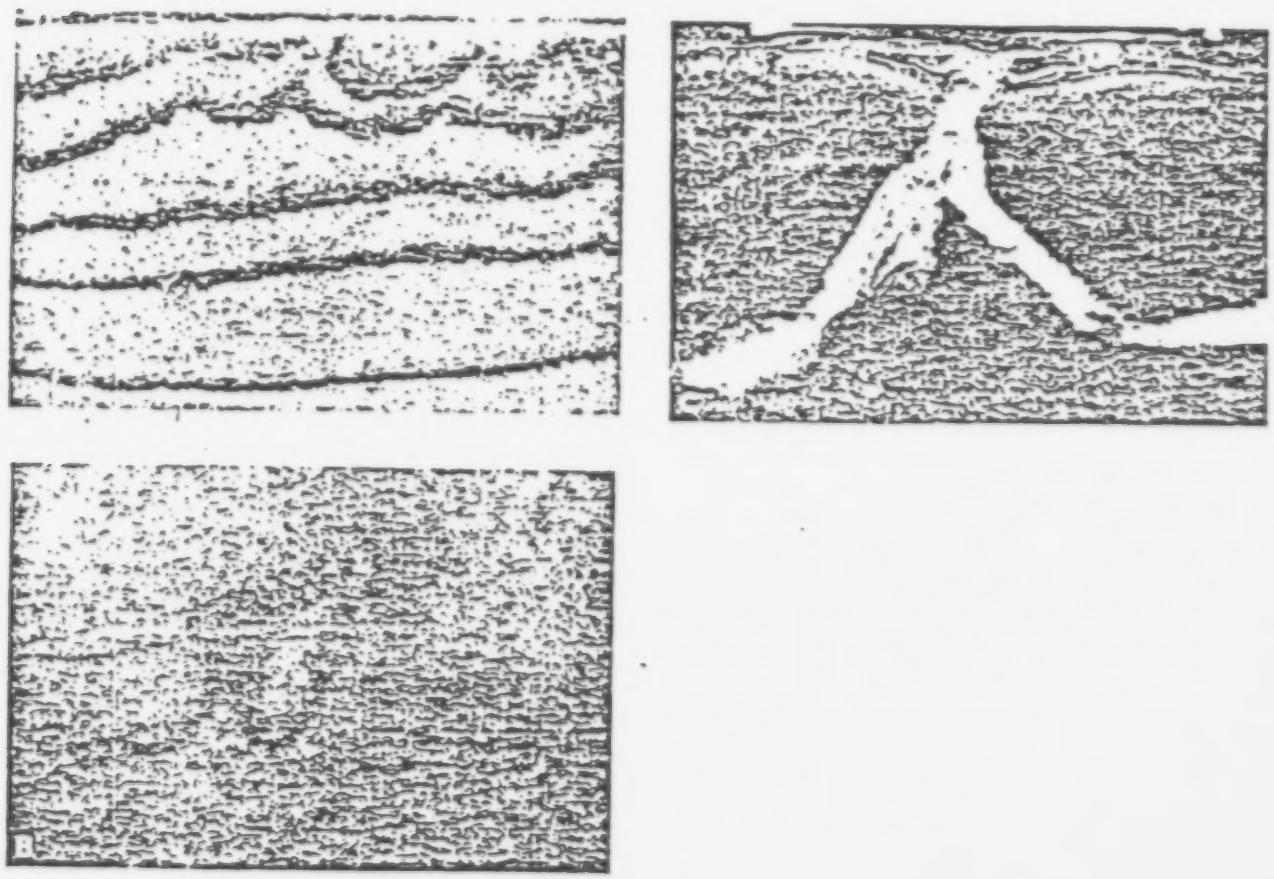


Figure 22 - Deformations in sand caused by water flow (Selley, 1969)

Period Since 1970

As indicated earlier, the late 1960s marked a major reduction in laboratory experiments on convolute laminations. We have selected only two articles for this period.

Anketell et al (1970) performed experiments dealing solely with sedimentary structures brought about by reversed density gradients. Moreover, the terminology had changed. There is reference to energy, forces and deformations, typical soil mechanics terms. The authors note that, while it is possible to demonstrate that little energy is required to initiate major deformations, the source of such energy is not always easy to identify. The laboratory experiments they did thus consisted of testing several preparations with different density gradients. Figure 23 illustrates the complexity of the deformations they obtained. In their conclusion, the authors observed that intraformational deformations can be obtained even in horizontal beds of sediments. They also illustrate the formation of breccias where the upper bed has a certain degree of rigidity (Figure 24).

The final article in this period is the one by Weaver and Jeffcoat (1978). In the laboratory, they reproduced the conditions required for the formation of sand volcanoes. Their results are given in Figure 25 and show that they also obtained pillow structures. These structures were produced by vibrations. The article is the only one in which mention is made of the force used to generate the vibrations - a hammer weighing 1,364 g, with which "moderate" blows were struck. It is clear that little is made of the kinds of vibration and acceleration given to the particles of soil or the degree of subsequent increase in interstitial pressure. We must examine documents relating to the dynamic behaviour of soils in the search for a better idea of the problem.

DISCUSSION

The survey of the literature on laboratory experiments has primarily concerned those which attempted to reproduce flexible deformation structures. In most cases reviewed, it seems that no attempt was made to simulate the process causing liquefaction as well. The data are more precise on the nature of the soil and its porosity. In no case has any attempt been made during an experiment to measure interstitial pressure for the purpose of a direct evaluation of effective stresses. Even where artificial liquefaction has been produced, the energy used is rarely quantified, such that, as Sims (1978) observed, it is difficult to know whether this energy can be compared to that occurring in nature.

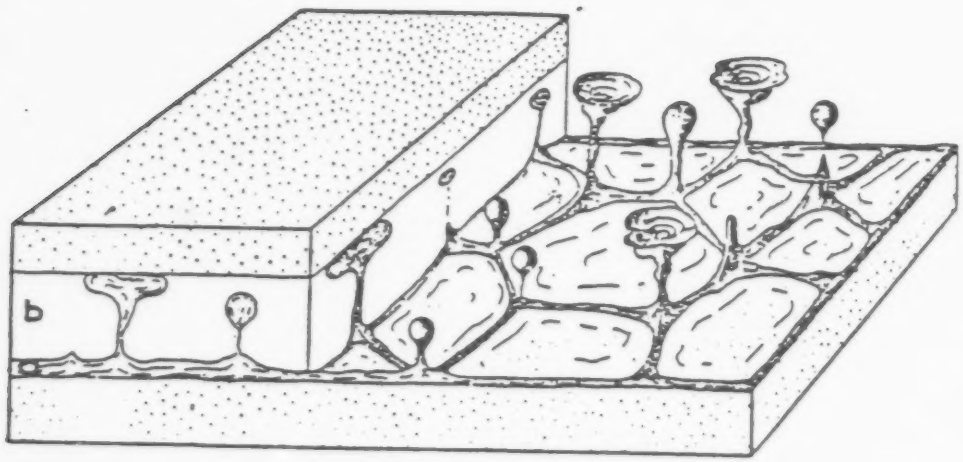


Figure 23 - Structures involving injection upward (Anketell et al, 1970)

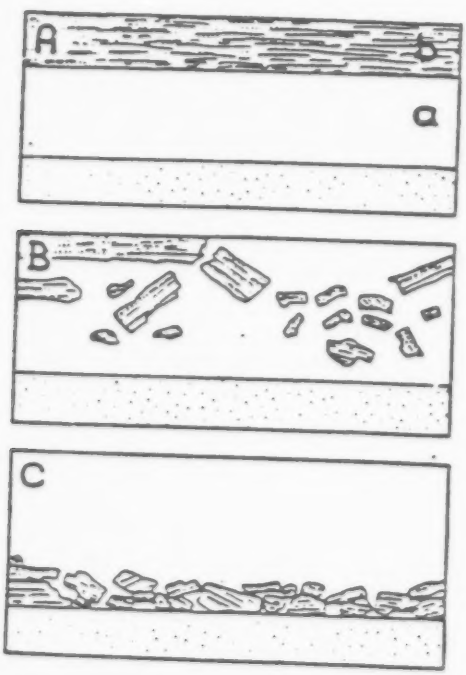


Figure 24 - Deformation in beds of which one (b) is fragile in its reaction and the other (a) is susceptible to liquefaction (Anketell et al, 1970)

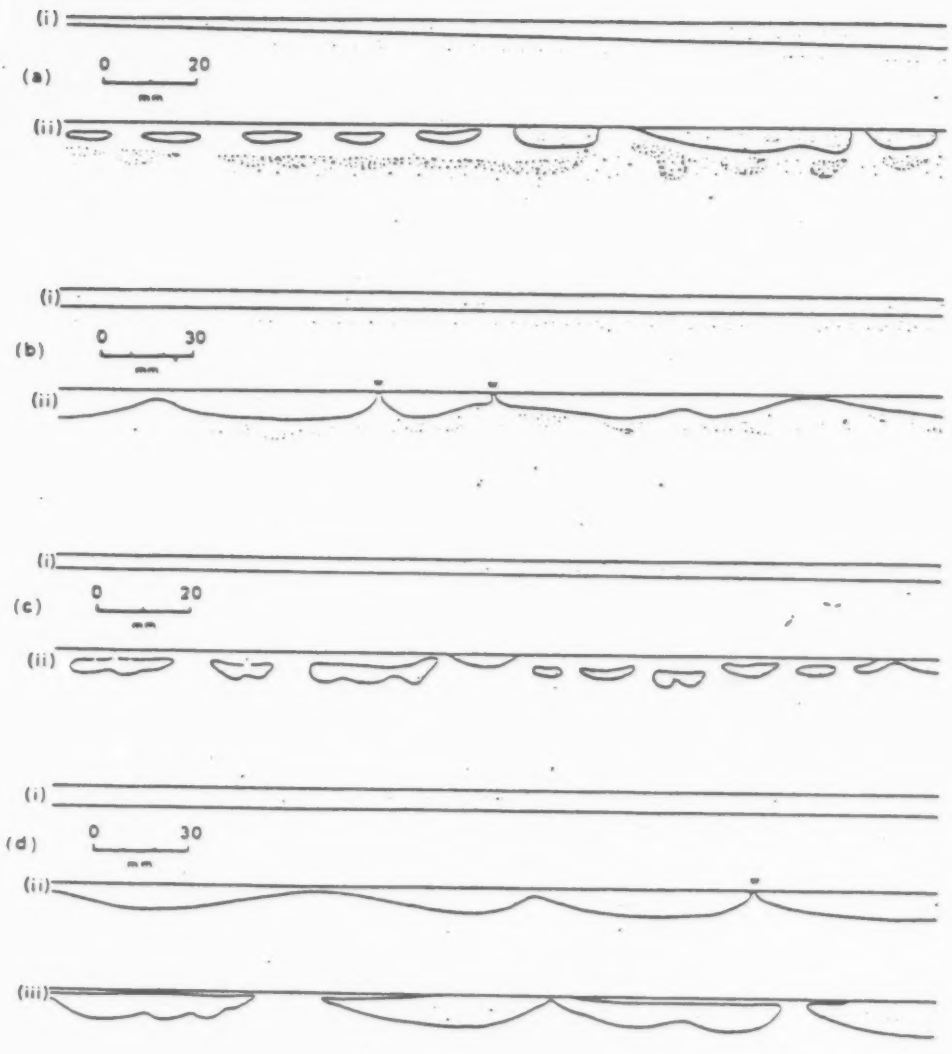


Figure 25 - Formation of pillow structures by vibrations in beds of sand (above) and calcareous clay (Weaver and Jeffcoat, 1978)

As Allen and Banks (1972) mentioned, the flexible deformations recorded may be a good indicator of seismic activity. However, several environments favour maintenance of high water content, such as the periglacial context. Laboratory experiments have resulted in flexible deformations such as convolute laminations, as well as sand dikes and mud volcanoes. All cases involved water-saturated soils which were fluidized or liquefied.

On the whole, the experiments done to date appear very incomplete in certain respects. For example, efforts up to the late 1960s were aimed primarily at reproducing deformations observed in nature by all kinds of methods. Subsequently, certain researchers realized that the processes involved could be complex, so they began computer simulations of the deformations observed. However, very seldom are we told how much energy is used to liquefy the sediment or what changes in interstitial water pressure take place during the experiment. It is therefore difficult to check effective stresses. Consequently, future experiments should not only simulate or reproduce field observations, but should also measure the control parameters in order to evaluate changes in the conditions of the experiment, compare them with field conditions and come to a conclusion about their appropriateness.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The bibliographical analysis has revealed a number of specific criteria which establish a link between certain types of deformation structures and seismic activity. These criteria are not absolute and can only be used to state probability. If these criteria are met, it is highly probable that a structure was formed by seismic activity. In addition, some general criteria help to identify seismic activity from a broader point of view.

Using specific criteria, we can link two types of structure to earthquakes: clastic dikes filled from below and sand volcanoes. These structures result from liquefaction of a bed of sand or silt and can be distinguished by such criteria as:

- connection to a source;
- internal structure;
- nature of material (granulometry);
- geometric relationships (dikes);
- degree of preservation (volcanoes).

Liquefaction is almost always caused by an earthquake, and this is how such structures are associated with seismic activity. However, other mechanisms can cause liquefaction; moreover, even if they only rarely come into play, their existence is an obstacle to the use of structures as absolute criteria of seismic activity. A number of authors have proposed more general criteria of seismic activity, also related to deformation structures. Some of these criteria cannot be applied in the local geological context, although others are useful. These are as follows:

- macroscopic indications of liquefaction (according to Wang et al, 1983);
- the presence of thixotropic phenomena (according to Coates, 1975);
- the horizontal continuity of deformed strata (according to Coates, 1975 and Sims, 1975);
- proximity of a source of current seismic activity (according to Sims, 1975);
- the presence of liquefiable sediments (according to Sims, 1975);
- the observations of deformation structures in a well-defined horizon (according to Sims, 1975).

Some of these criteria have already been met (such as proximity of a source of current seismic activity, macroscopic indications of liquefaction and the presence of liquefiable sediments), but it would be helpful to verify them systematically. Other criteria should apply (such as horizontal continuity of strata and observation of structures in a well-defined horizon), but this remains to be verified by field studies designed for the purpose.

RECOMMENDATIONS

In accordance with the results obtained, it is appropriate to make recommendations on the nature of work and studies which could be undertaken to further our understanding of regional seismic activity. Some recommendations

are academic and are intended to correct certain weaknesses found during analysis of the texts.

- Review the terminology used by researchers. There appears to be some confusion resulting from the variable use of terms by different authors. It would be helpful to clarify ambiguous usage and to propose terminology that is either genetic or descriptive, or both.

- Establish an adequate classification of deformation structures. This subject is a thorny and difficult one, but is worth pursuing.

Other recommendations are more specific and are mainly concerned with the objectives of the project.

- By means of field studies, check the validity of the specific and general criteria selected.

- Evaluate liquefaction structures macroscopically, using aerial photographs. A number of liquefaction indications have already been observed and others could be found. The use of aerial photographs (from around 1930) could prove useful.

- Locate structures, such as clastic dikes and sand volcanoes, and excavate them to check for the selected criteria.

- Verify the presence of sediments that are liquefiable by known processes. A project of this nature is currently under way in the Quebec City region, under the direction of the Groupe de Géologie de l'ingénieur of Laval University, and results so far are positive.

- Reworked or deformed horizons should be subjected to detailed stratigraphic studies to establish correlations on a regional scale and date old indications of seismic activity.

The range of future work is so vast that much of it will be difficult to accomplish. Judgment must therefore be used in selecting avenues of research that will lead as quickly as possible to the desired objective - a more thorough understanding of regional seismic activity.

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APPENDIX I

CLASSIFICATION - CODES

Group	Code	TYPE OF DOCUMENT
1	A	BOOK - TEXT BOOK - TREATISE
	B	ARTICLE
	C	TECHNICAL NOTE
	D	RESEARCH REPORT (SPECIAL PAPER - Thesis)
	E	ABSTRACT
	F	OTHER
		NATURE OF DOCUMENT AND WORK
2	A	DESCRIPTIVE
	B	ANALYTICAL - THEORETICAL
	C	EXPERIMENTAL
	D	MECHANICAL ANALYSIS - LABORATORY
	E	GEOTECHNICAL
	F	GEOPHYSICAL
	G	OTHER
		NATURE OF DEFORMATION REFERRED TO
3	A	PENECONTEMPORANEOUS (SYNDEPOSITIONAL)
	B	INTRAFORMATIONAL
	C	POST-LITHIFICATION
	D	AFFECTS ONE BED
	E	AFFECTS MORE THAN ONE BED
		TYPE OF DEFORMATION REFERRED TO
4	A	CONVOLUTE LAMINATIONS, LAMINAE
	B	CONTORTED BEDDING, CROSS-BEDDING
	C	BALL-AND-PILLOW, NODULES, PSEUDONODULES
	D	LOAD CASTS
	E	FRACTURE, FAULT, FISSURE
	F	MAJOR FOLDS
	G	SAND VOLCANOES, MUD VOLCANOES
	H	CLASTIC DIKES - FILLED FROM ABOVE
	I	CLASTIC DIKES - FILLED FROM BELOW
	J	DIAPIRS
	K	SLUMPING - SLIDING (incl UNDER WATER) SLUMP STRUCTURES
	L	OLISOSTROMES
	M	TURBIDITES
	O	ICE WEDGES - FROZEN-GROUND STRUCTURES
	P	COMPACTION
	Q	CYLINDRICAL STRUCTURES ("SAND PIPES")
	R	BOUDINAGE

MATERIAL AFFECTED

5	A	UNCONSOLIDATED
	B	CONSOLIDATED (NON-LITHIFIED)
	C	LITHIFIED
	D	PLEISTOCENE DEPOSIT
	E	PRE-PLEISTOCENE DEPOSIT
	F	CLAY
	F	SAND - SILT
	H	GRAVEL
	I	OTHER (coal)

ORIGINAL OF DEFORMATION

6	A	GLACIAL PHENOMENON - PERIGLACIAL - FROST
	B	LIQUEFACTION
	C	SEISMIC WAVES - SEISMIC SHOCK
	D	EFFECTS OF DENSITY
	E	EFFECTS OF GRAVITY (compaction -)
	F	EFFECTS OF CURRENTS, WAVES
	G	TECTONICS
	H	MAGMATIC INJECTION
	I	EFFECTS OF PRESSURE
	J	DESICCATION
	K	GAS
	L	NOT MENTIONED

REGION IN WHICH PHENOMENON IS OBSERVED

7	A	HAS UNDERGONE GLACIATION
	B	HAS NOT UNDERGONE GLACIATION
	C	GLACIATION NOT MENTIONED
	D	AREA OF SEISMIC ACTIVITY
	E	AREA WITHOUT SEISMIC ACTIVITY
	F	SEISMIC ACTIVITY NOT MENTIONED

COMMENTS

8	A	DESCRIPTION OF DEFORMATION (amplitude, wavelength)
	B	IF VIBRATIONS, MAGNITUDE OF EARTHQUAKE - DURATION
	C	MATERIAL - WATER CONTENT - INTERSTITIAL PRESSURE
	D	LABORATORY EXPERIMENTS - TRIAXIAL - BOX SHEAR APPARATUS
	E	VALUES MEASURED (susceptibility, shear resistance)
	F	MENTIONED CLASSIFICATION OF DEFORMATIONS
	G	MENTIONS CRITERIA